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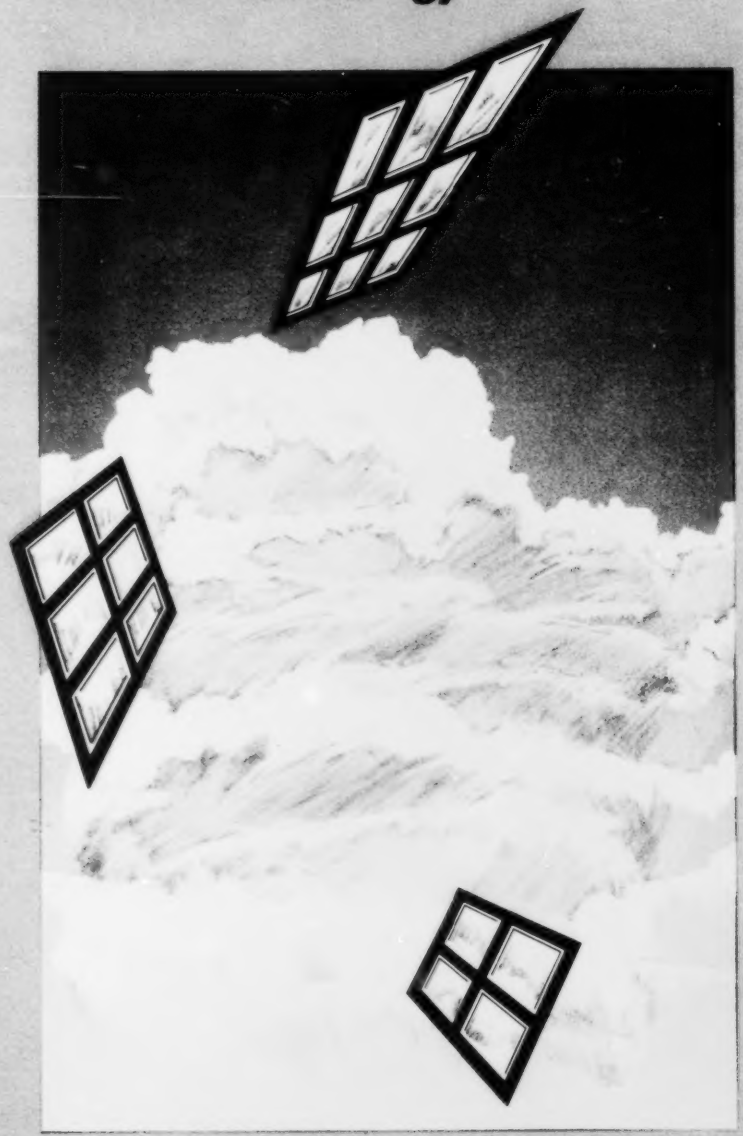
Window Performance and New Technology



PROCEEDINGS OF BUILDING SCIENCE INSIGHT '88

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Window Performance and New Technology

Proceedings of Building Science Insight '88

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This publication contains the proceedings of Building Science Insight '88, a series of one-day seminars on windows held in cities across Canada in the fall of 1988. Building Science Insight '88 was the 28th since IRC began its annual series of seminar–workshops in the sixties. Seminars were held in St. John's, Halifax, Moncton, Quebec City, Montreal, Ottawa, Toronto, London, Winnipeg, Regina, Edmonton, Calgary, Kelowna and Vancouver.

Appreciation is extended to Armand Patenaude, president of Air-Ins Inc., a building components testing laboratory affiliated with the Trow Group. Members of the Canadian Window and Door Manufacturers Association and the Insulated Glass Manufacturers Association of Canada also made valuable contributions to the afternoon discussions.

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Windows: Overview of Issues

M.Z. Rousseau

What Is a Window?

Windows play a significant role in achieving quality of life and comfort in buildings. For the occupant, windows bring natural light and solar heat, fresh air and a view to the outside world. For the architect and designer, windows shape the facade, interrupt wall or roof systems and require special detailing at their interface. For the mechanical engineer, they are sources of overheating, cooling or air infiltration. For the builder, windows are locations where many dissimilar materials and trades have to join together. For the fire engineer, windows can be an exit in case of fire, a potential path for flame propagation to other storeys or buildings, and a source of air to the fire. For the consultant, they may well be a source of revenue because windows can be associated directly or indirectly with performance failures. As one can see, windows mean different things to different people. But yet, what is a window? Like any part of the building envelope, a window is a filter of conditions between inside and outside, with the addition that it can be operable and to some degree transparent to natural light. A window can be described as anything one can see through: the glazing system of a residential patio door or a commercial curtain wall, a skylight, sloped glazing and, of course, the conventional window above your kitchen sink.

Never has there been a larger variety of windows on the market. This is due to the many combinations of glazing, coatings, sash and frame materials and profiles, and the options offered by emerging technology. This series of papers relates mainly to factory assembled systems that are placed in the building envelope; some of the performance issues discussed will, however, apply to site assembled or glazed systems. This paper examines the nature of the requirements for windows from three points of view: a window as a system of elements, as part of the building envelope and as part of the indoor environment. It also describes briefly the current array of windows and window components on the market. The second paper, *Window performance factors*, examines the performance requirements to consider in the process of window selection. The third paper, *The system approach to window performance standards*, concentrates on the Canadian standard on windows and reviews its current features and testing procedures, as well as future possible additions. The fourth paper, *Integrating the window with the building envelope*, looks at the installation of windows in walls of commercial and residential buildings and how to ensure continuity of functions at the wall–window interface. The last paper, *New technology in the window industry*, introduces the emerging technology such as structural glazing, low emissivity coatings and gas-filled sealed glazing units.

What Affects Window Performance?

The three broad aspects of window performance are the physical characteristics of the windows as an assembly of building materials each of which performs various functions, the physical interface with the enclosure which it becomes part of, and the effects of windows on the quality of the indoor space and the comfort of occupants.

Windows are probably the most common factory-assembled component of the building envelope. As such, they are an assembly of materials that, as a system, have to perform the same functions as opaque walls, and more (Figure 1). In addition to controlling heat flow, sound transmission, and air and rain leakage, windows are expected to transmit light without causing glare, to bring in fresh air without causing drafts and letting in insects, to be airtight but easy to operate, to bring in solar heat (in housing) in winter but not in summer. That makes their design and performance evaluation

rather complex procedures. Some windows have better performance than others even though they might all meet the Canadian standards. For example, the Canadian standard on windows[1] has three levels of performance for some requirements. It is up to the specifier to decide which severity of laboratory conditions is likely to be closest to the actual field conditions. The specifier may even have to require a level of performance higher than the top level specified in the standard; for example, wind pressures accompanied by rain in the Maritimes can be higher than what windows are presently required to be tested for in the Canadian standard on windows. Moreover, the standard does not cover all performance criteria; thermal resistance and sound transmission are examples of issues not covered. Assessment of condensation potential is only required for aluminum windows, even though a badly designed window can cause undesirable condensation regardless of the framing material. Unless windows are evaluated for these requirements, it is difficult to make a proper comparison between products. The many performance aspects of a window as a system of parts are examined in the second and third papers, with particular emphasis in the latter on Canadian standards that apply to windows and their components.

Once the windows are selected, the next step is to detail the connection to the main body of the enclosure. The need for proper detailing of the window–wall interface cannot be overemphasized. This junction is often involved in problems showing up in the walls or on the window. In walls, air exfiltration can cause efflorescence on brick cladding, or icicles emerging from joints between precast concrete panels, or rotting of a wood-frame wall under windows due to the penetration of 'liquid condensate' into the wall during a mild spell in winter. Air infiltration in mild weather can induce rain penetration, which shows up at the head of the window (some must penetrate at the sill too, but it 'just' gets into the wall, and does not show up inside). Cold air infiltration can cool inside surfaces below the dew point temperature of the inside air and hence promote surface condensation. Discontinuity of insulation, air infiltration at the wall–window interface (Figure 2) and positioning of the window vis-à-vis the cold materials of the wall can cool down the edge of the framing elements, increase surface condensation and in some cases increase potential for thermal breakage. Contrary to common belief, a proper weathertight connection does not mean merely caulking the outside face of the window frame to the cladding and stuffing fibrous insulation in the cavity. The mechanical connection of the window to the rough opening in the wall is also crucial to the proper transfer of wind loads to the structure. Airtightness is the key to interstitial condensation and rain penetration control; estimation of joint movement for proper selection of sealing materials is one of its critical aspects. Flashings, rain deflectors, and cavity drainage complete a proper approach to the installation of windows. These issues and more are treated in the fourth paper.

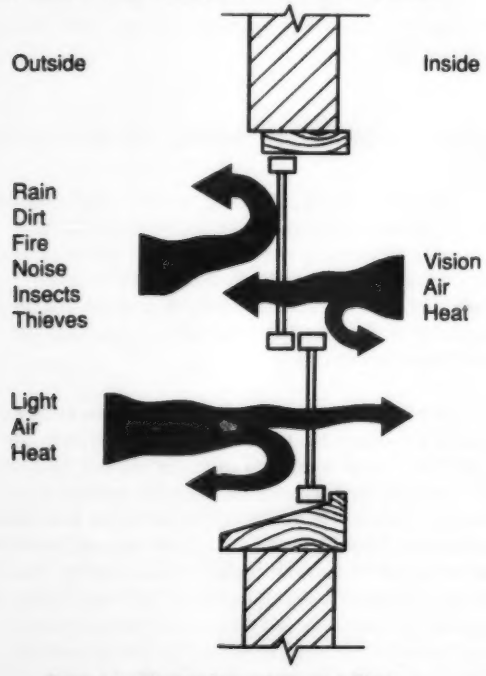


Figure 1. The window system as a filter.

Windows also affect the indoor environment. Their thermal and optical characteristics, size, orientation, openability and treatment with shading devices have an impact on the comfort of occupants and the operation of mechanical systems. Glare, overheating and cooling effects, draughts and outside noise affect the physical comfort of occupants, while their psychological comfort can also be affected by communication — or lack of it — with the outside world. How much glazing, what type and where to place it to satisfy the occupants should be accounted for in the evaluation of design options. (Comfort and user satisfaction are becoming accepted as intrinsic parts of the total building performance and windows certainly affect this. However, this aspect of window performance is beyond the scope of this series of papers.) The heating, cooling, humidification and lighting of the space are prime examples of systems affected by window design and operation. For example, operable windows are the nightmare of mechanical engineers, even though they mean paradise on earth to the occupants, who feel more in control of their environment. Moreover the installation of tighter windows in existing buildings affects the indoor climate: mechanical ventilation rates may have to be increased to account for the reduction in air leakage, humidifiers may have to be turned down and heating systems may become oversized.

What Are the Requirements for Windows?

Expectations of windows have increased over the years and yet the conditions of exposure have become more severe. Our grandmothers lived in houses with draughty windows in a dry environment; now we want humid houses with no condensation on energy-efficient windows at a reasonable cost.

As one can see, these demands not only relate to the windows but to the environment they create inside. The performance requirements for windows are as follows:

- control heat flow,
- control air flow,
- control water vapour flow,
- control condensation,
- control rain and snow penetration,
- control solar and other radiation,
- control sound transmission,
- prevent the entry of insects,
- control fire propagation,
- be usable as fire exits all year long,
- prevent forced entry,
- be easy to operate by all groups of users,
- provide strength and rigidity,
- maintain satisfactory performance over service life,
- be appealing and harmonious with the surroundings,
- be economical.

Most performance requirements for windows as a system are briefly described below.

Heat Flow

The control of heat flow is a complex task. Heat can flow from outside to inside during sunny and warm days; this increases air-conditioning costs (if applicable) and inside temperature. There can also be heat leaving the building from inside; how much depends on the thermal resistance of the window components. The thermal resistance of the glazing comes from the air space between the panes of glass and from the thin films of air at the inside and outside surfaces of the assembly that slow down the heat transfer (Figure 3). The glass itself has negligible resistance to heat flow. Coatings of low emissivity applied on glass or plastic to reduce the flow of heat radiating from objects and people inside, and gases other than air to fill the cavity of sealed glazing units are the most recent available developments for increasing the RSI value of glazing.

Many new products to control solar radiation have entered the market over the last twenty years. Heat-absorbing glass and reflective coatings on glass responsive to a particular wavelength of the solar energy spectrum are mainly used in commercial buildings, but coatings reducing the entry of ultraviolet radiation, which fades fabrics, are gaining popularity on the residential market. As discussed in the second paper,

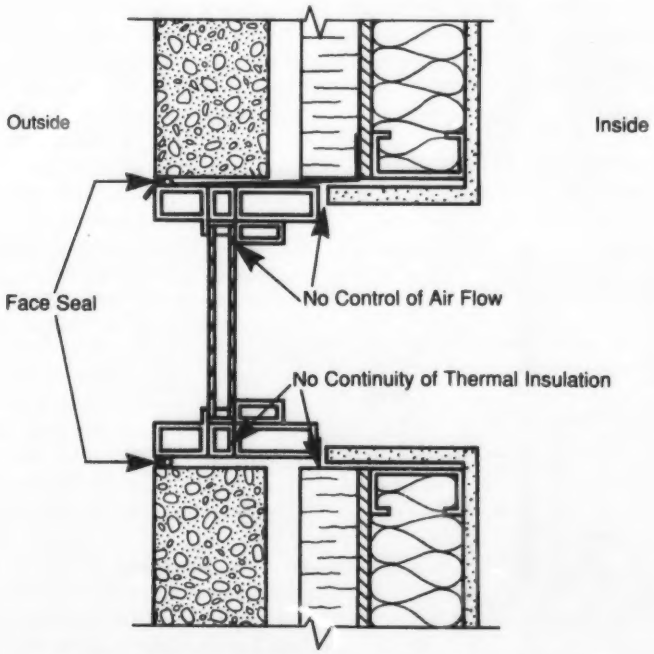


Figure 2. Discontinuity of functions at wall–window interface.

glazing is used as an energy filter, whether it is solar energy, radiation energy from objects and people or sound wave energy.

In some cases (in heritage buildings, for example), windows may have to be retrofitted rather than replaced. In order to improve their thermal performance, adhesive films may be applied on the existing glass to control solar heat gains and reduce internal heat losses.

Air Leakage

Windows must resist air leakage, which affects energy control, comfort and condensation potential. Since the materials themselves have rather low permeability to air, the junctions between materials are the main areas requiring attention. Sealants and gaskets are used for the fixed parts of the window, while weatherstrippings are used for the operable parts of the window.

At the glazing–sash junction, wet or dry seals are used; they should be compatible with the sealing material of the sealed glazing unit. In wood windows, wet seals are commonly used. Sealants are generally applied as cap beads at the outside of the joint; the application of similar seals on the inside of the joint as cap and heel beads is equally important (Figure 4). The heel bead is actually the sealant ensuring airtightness of the assembly; the others control direct water entry from rain or condensation. In vinyl and aluminum sashes, dry and wet seals are used: a rubber-like grip can be installed as a cap seal on one or both sides of the glazing unit and a heel seal provides airtightness between the glazing and the sash (Figure 5). The heel seal is not part of all window designs on the market and therefore can be used as a selection criteria.

For the operable parts of the window (the sash–frame junction), a large variety of weatherstrippings are commonly used. The shape and material used depends upon the mode of operation of the window. For example, in a pivot window (casement or awning), the weatherstrippings can be tubular and made of plastified PVC or a synthetic rubber like EPDM (ethylene propylene diene monomer), or a straight strip of material can be used. There are a variety of shapes but they all work on the same principle; the material is compressed as the sash is closed. In sliding windows, angle strips made of metal, PVC or EPDM, and synthetic brushes are generally used.

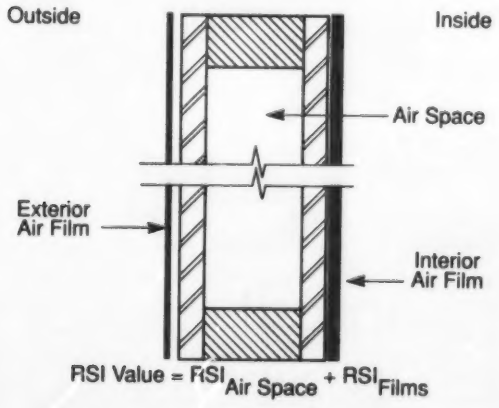


Figure 3. RSI value of double glazing.

Water Vapour Flow

The control of water vapour flow through a window is linked to the control of air flow, since vapour diffusion in most window materials (aluminum, steel, glass, PVC, protected wood) is very small. For example, in unsealed double glazing, exfiltrated humid air can condense between the panes of glass (Figure 6). A better tightening of the existing inside sash or, as a default, a slight opening of the exterior sash can reduce the extent of the problem.

Condensation

The control of condensation is also important: not only does it impair visibility but the liquid condensate can deteriorate sash, frame and sill as well as the interior finish and the supporting wall. When the temperature of a surface falls below the dew point of the inside air in its vicinity, moisture will condense on the surface. Condensation on windows may be a more common source of complaints in housing than in commercial buildings. Relative humidity of inside air and the temperature of the glazing, sash and frame are the two elements to act upon in order to solve the problem. In order to reduce the moisture level in the inside air, the moisture sources (human activities, humidifiers, soil, wood for heating, etc.) have to be reduced and/or the ventilation has to be increased. To increase the temperature of the inside surface of the windows, many strategies can be used. The RSI value of the window component can be increased by the addition of another air space, which is formed by a glass or plastic layer, inside, tightly covering either the whole window or the glazing only. The warm air inside the room can be better circulated next to the windows, with fans or by removal of barriers (heavy curtains, air deflectors, large furniture) in front of windows and warm air registers or radiators.

The installation of tighter windows in an existing building increases its airtightness, which in turn increases the relative humidity inside. Subsequently, this increases the condensation potential on the new

windows. By performing better than the previous windows, they have become more vulnerable to condensation. The real explanation is often a disturbed balance between the rates of ventilation and moisture generation, and the lack of recognition of the interaction between building systems.

Rain Penetration

Rain penetration can be controlled by applying the rain screen principle to the interface of glazing–sash and sash–frame components. The rain screen principle is based upon the control of the forces that can move water through small openings, rather than the elimination of the openings themselves. The kinetic energy of rain drops, gravity, capillary action and air pressure difference are the forces that can lead to water penetration through small openings. Since an air pressure difference between the outside and the air pockets within the window assembly is a significant force causing air infiltration, which pushes water in, better control of such a pressure differential reduces rain penetration. For equalization of the air pressure in the cavity of these interfaces with that of the outside, there must be an air seal on the inside of the cavity and a rain deflector on the outside; the cavity must communicate with the outside air and must be drained (Figures 7a and 7b). However some window designs are based on the 'face seal' approach (no air seal inside), which consists of

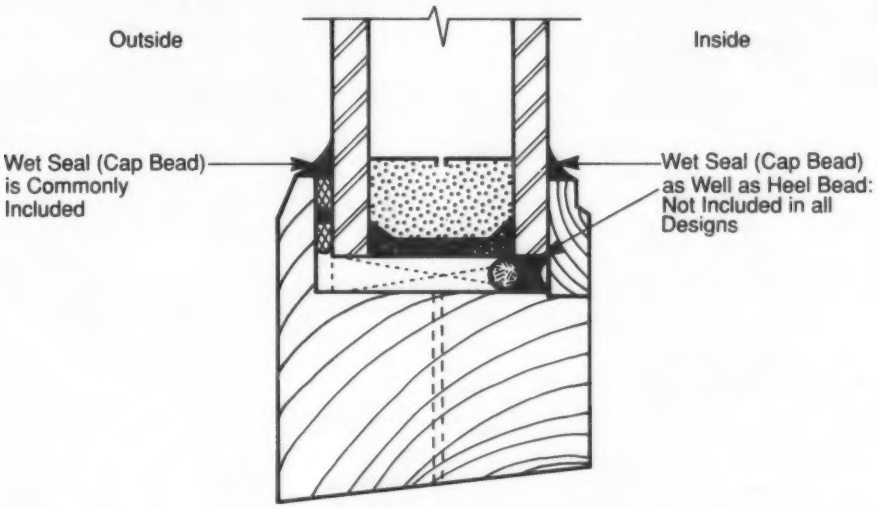


Figure 4. Wet seals in wood sash–glazing junction.

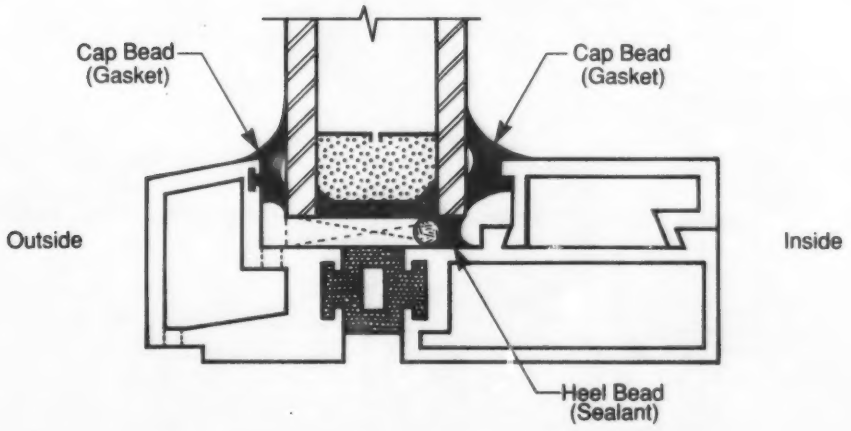


Figure 5. Dry and wet seals in aluminum sash–glazing junction.

sealing all the openings at the outside face of the window components rather than controlling the forces that would push water through them. This can work for some time but will require frequent maintenance over its service life.

Sound Transmission

The control of sound transmission through windows requires large cavities between layers (multiple glazing), heavy layers (thicker glass) and reduction of the structural connection between layers (separate frames and sashes for inner and outer layers). They certainly have to be as airtight as possible: usually fixed windows provide much better sound transmission control than operable windows.

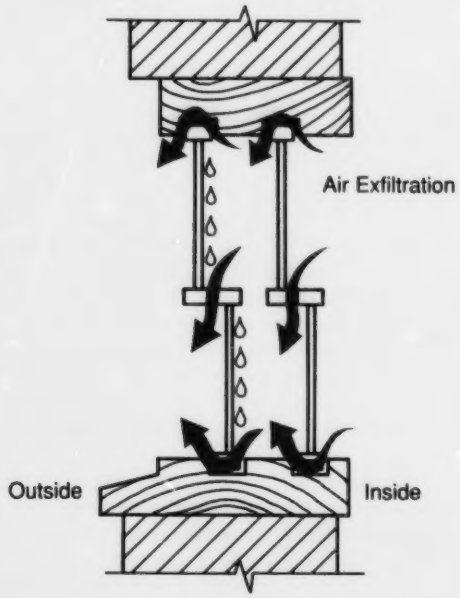


Figure 6. Condensation between panes of unsealed glazing.

Entry of Insects

When windows are operable, screens must be provided to prevent the entry of insects. The fitting of the screen is critical to prevent insects from getting in. The Canadian standard on windows requires the frames of operable windows to be designed to receive screens intended for use with the windows; however, there is no requirement on how they should fit in the frame. Observation and common sense will indicate the ones that do not let bugs crawl around and are easy to remove and reinstall for cleaning.

Ease of Operation

The ease of operation of windows sometimes conflicts with the requirement of air and sound tightness. With an aging Canadian population, it is important to design windows for people with less physical strength. The mechanism of operation of the window and its hardware, as well as the thermal and moisture movement of the sash and frame materials, affect the 'operability' of the window.

Strength and Durability

Glass is a brittle material and fails in tension. Even though its potential tensile strength is 6900 MPa, failure occurs at stresses far below this value because of surface

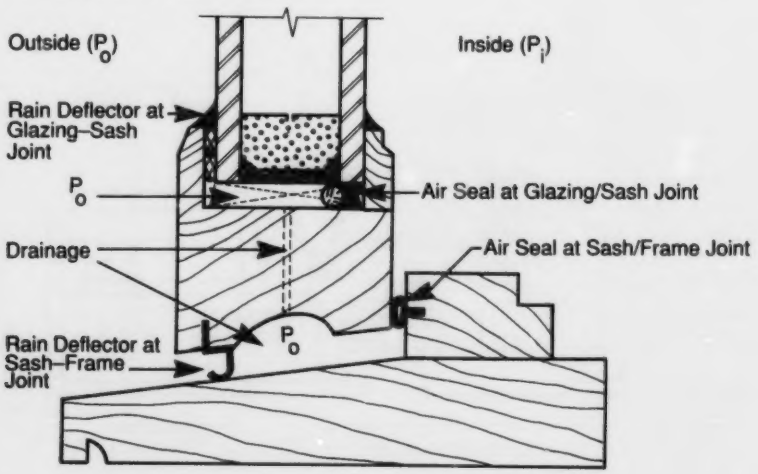


Figure 7a. Rain screen wood window, vertical section at sill.

imperfections; some of these are inherent to the manufacturing process of the glass and some are mechanically induced. In order to provide strength and resistance to breakage, and ensure that glass that breaks does not fall out of its frame, fully tempered, heat-strengthened, wired and laminated glass have been developed.

Fully tempered glass is basically a stressed skin sandwich; both surfaces are in compression and the core is in tension. The glass is strengthened by heating it to near its softening point, then chilling it rapidly. The surfaces cool and contract while the interior of the glass is still warm. When the interior shrinks, the surfaces are rigid and are compressed by the contraction of the interior. Therefore any tension stress imposed on the glass has to overcome the initial compression stress prior to affecting the glass in tension; that results in a glass three to five times more resistant to failure by bending, impact or thermal stress than annealed glass. The weakness of tempered glass is its edges: a light impact with a sharp object can cause its failure. It also has to be cut to size before being tempered because cutting after tempering results in shattering of the sheet.

Heat-strengthened glass receives a heat treatment similar to that used for fully tempered glass but the temperature and rates of cooling produce a lower level of surface compression. It is suitable for applications where annealed glass could be used but where additional strength and thermal endurance are desirable.

Wired glass has a wire mesh embedded in the molten glass during the manufacturing process. It is considered half as strong as float glass of the same thickness and cannot be tempered or heat-strengthened. Its main advantage is provided by the wire, which holds the pieces of glass together after fracture has occurred. Wired glass is used in fire separations, for burglar protection and where protection from flying glass is required in high risk areas.

Laminated glass comprises two or more sheets bonded together with intermediate layers of plastic. Laminated glass is no more resistant to fracture than monolithic glass, but in case of fracture, the plastic interlayer holds the fragments in place.[2] A combination of glass and interlayers can be designed for such uses as sound control, solar heating control, bullet-resistance and blast-resistance.

Fire Propagation

Because glazing is considered a weak point in the envelope for the propagation of fire to other storeys or other buildings, the National Building Code limits the area of windows according to the occupancy of the space, the distance from the lot line, or the limiting distance and the geometry of the facade. New developments on sprinklered windows for the prevention of fire propagation will be presented in the fifth paper, *New technology in the window industry.*

What Are the Requirements for the Wall–Window Interface?

The detailing of the wall–window interface is critical to the continuity of functions over the enclosure. Unfortunately, this is usually the 'grey zone' at the design and construction stages. Too often these details are left to the last minute, after the windows have arrived on site and it is time to install them. The little

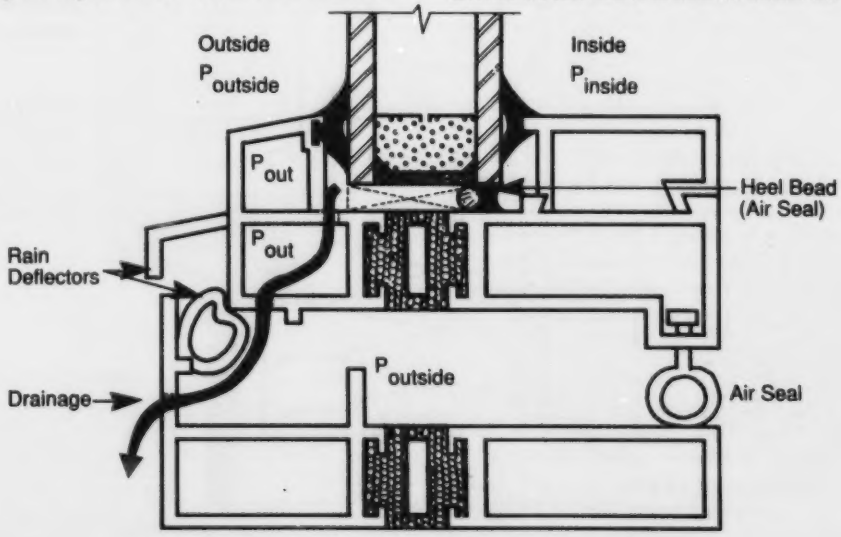
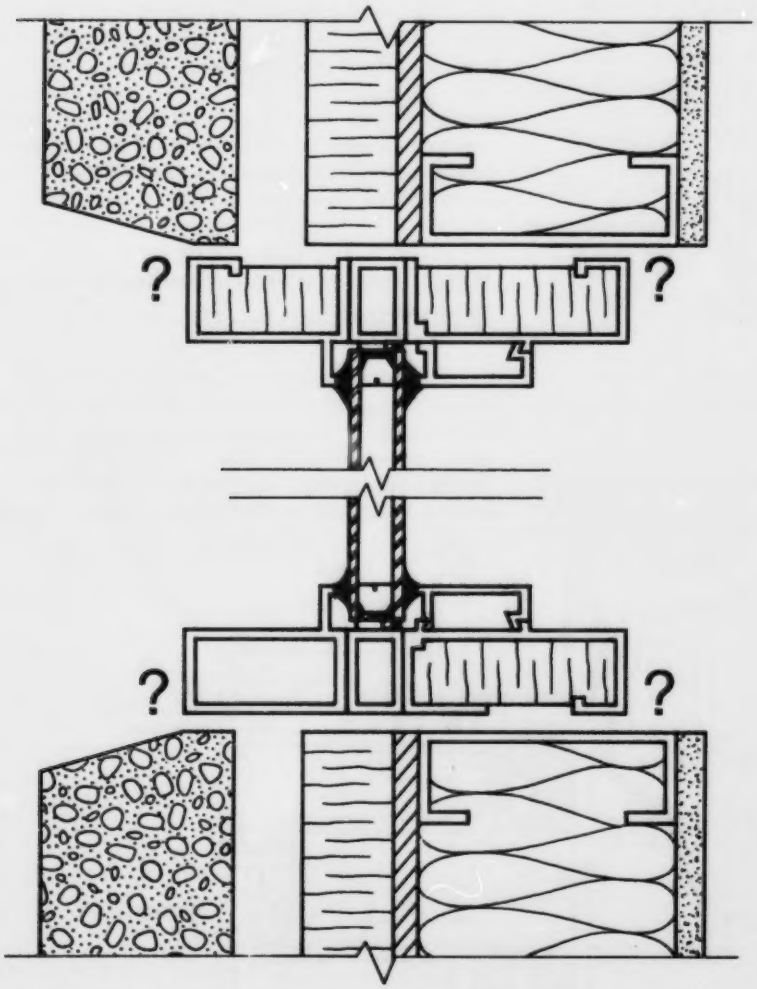


Figure 7b. Rain screen applied to aluminum window.

'gap' between the rough opening and the window frame can threaten the performance of the whole system but for some reason, it does not get its share of attention. Problems of rain penetration, air infiltration or efflorescence on masonry can relate to a lack of continuity of the functions of the envelope around windows (rather than through them). The plane of airtightness in the window and in the walls must be clearly identified by the designers so that the two appropriate components get joined together properly (Figure 8). Besides sealants and compressible gaskets, new families of products are gaining popularity. Adhesive elastomeric membranes used as wall air barriers in highrise construction also make the interface with the window frame airtight. By extension, strips of these membranes join other materials acting as wall air barriers to the window frame. Sprayed-on polyurethane foam (PUF) insulation is also used because it can provide both thermal insulation and airtightness; however, the movement PUF can accommodate, its adherence to various substrates and the potential transfer of the vertical loads above the window in case of wall settlement have to be addressed.

The rain screen principle can also be applied at the interface between walls and windows in order to achieve low maintenance of the joints and better performance. Besides discussing ways to make the wall–window interface weather-tight, *Integrating the window with the building envelope* discusses the mechanical attachment of the window to the wall and its implications to the



- *What is the wall air barrier?*
- *Where is the plane of airtightness in the window?*
- *Will the rain screen principle be applied or the face seal approach be taken?*
- *How large should the joint be, and what materials should be used to seal it?*

Figure 8. Window–wall interface: what and how to join together.

movement of the joint. The structural connection between the window and the wall is critical to the proper transfer of wind and other loads to the structure. Most often, the head of the window is not attached in any way to the header; this tends to increase the potential displacement of the window frame relative to the rough opening. The locations of anchor points also affect the expansion and contraction of the joint and the selection of the sealing materials.

The installation of replacement windows in existing construction is probably more complex than installing windows in new construction because one has to deal with what is there, and one does not always know what is there before decisions are made. For example, the wall–window interface should be airtight and this implies that a plane of airtightness exists in the wall itself, which is unlikely in most older buildings. What do you join the window frame to? This difficulty probably explains why so many retrofitted buildings have been 'face sealed' on the outside without any type of inside sealing; new windows may well suffer from rain penetration because of that compromise. In existing buildings (commercial, residential and institutional) where wood windows are replaced, the decision to keep or remove the existing wood frame, and to insert the new window frame in the rough wall opening or in the existing frame is important (Figure 9). Often the new frame is inserted into the old one, and everything is covered on the outside with an aluminum sheeting and face sealed. This means the rain screen principle is not applied and the size of the gap around the window has doubled, resulting in increased air leakage at the wall–window interface.

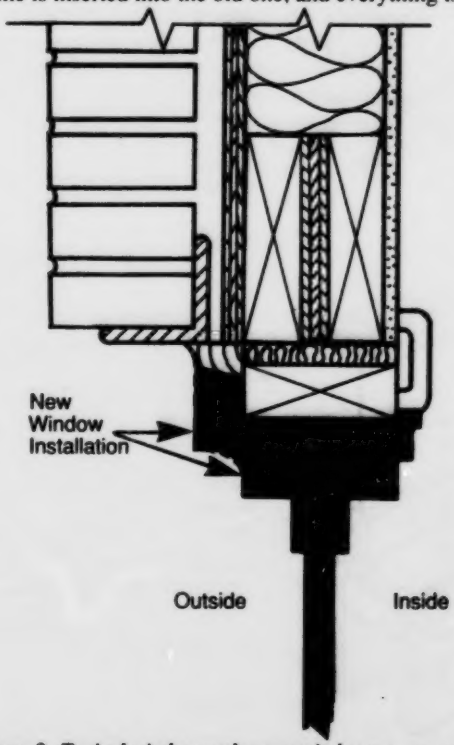


Figure 9. Typical window replacement in houses: no rain screen, no airtightness.

An understanding and appreciation of what has to be achieved, of the sequence of construction, and of the way to design the details so they are buildable are of prime importance. The trades putting it together also have to understand why it is so important to do it this way rather than the way they have been doing it for years. To make sure the window performs as intended, a mock-up can be tested in the laboratory to evaluate if it can work, and on site to verify whether it is being built to the specifications.

What Makes Windows?

Windows are just about as old as civilization itself. The Assyrians several centuries before Christ had long, narrow windows divided by little columns. The Egyptians depicted windows in their early wall paintings, and there are windows in the fabled temple at Karnak built by Pharaohs Seti I and Ramses II. In just about every case, the windows were only openings in walls, covered occasionally with hides, drapes, or matting. Not until the height of Roman architecture did windows actually start looking like windows. Ordinarily, the Romans glazed their windows with sheets of mica, panels of seashells, even thin sheets of translucent marble.[3] By the tenth century, there was fairly high production of window glass in northern Europe, probably encouraged by the dictates of the climate.

The basic parts of windows as we know them are the lights, the glazing, the sash, the frame, the sealants and weatherstrippings and the hardware (Figure 10).[4] The lights are the transparent portion of the window, made of glass or plastic. The glazing is the assembly of multiple lights and their connections. The sash holds the glazing and is the operable portion of the window. The frame holds the sash and is mechanically connected to the wall or the roof. The weatherstrippings and sealants ensure some tightness against air, rain, snow, vapour flow and sound transmission at the interface between materials, while the hardware ensures the operation and locking of the sash.

Glass

Glass is a brittle material made from the fusion of silica. The glass used for most windows is called soda-lime glass because these are the predominant compounds combined with silica. Glass used in Canada for

glazing is produced by the float process. Since the sixties, *float* glass has replaced *sheet* glass, which was more wavy and caused visual distortions. In the float glass process, the molten glass floats on molten metal, where it flows to a uniform thickness. When the sheet is drawn off, both surfaces are flat and parallel. After being formed into a continuous ribbon, the glass is cooled gradually to room temperature in a continuous annealing oven. This removes most of the stress that may be present and leaves the glass essentially free of residual stress. A*nnealed* glass may be subsequently cut. Most flat glass is sold in the annealed state.[2]

Plastics

Some plastics are attractive materials for use as glazing because of their light weight, ease of handling, light transmission, and better shatter resistance than plain glass; they permit greater freedom of design. Plastics are mostly used in locations where resistance to chemicals is required or a high breakage rate makes use of glass costly. Plastic is not unbreakable; a hard blow can cause breakage, but into large, dull-edged pieces rather than the sharp fragments that may fly from a smashed glass window. Acrylics, polycarbonate (PC), poly(vinyl chloride) (PVC) and glass fibre reinforced polyester (GRP) are the most widely used.

The initial light transmission coefficient of a few plastics is compared to that of glass in Table 1.[5] The optical properties of plastics are affected by the loss of surface quality, due to scratching during service or natural weathering. Natural weathering often causes deterioration of optical properties through discoloration, pitting, microcracking, surface erosion, leaching of ingredients and chemical or photo–chemical degradation. Because these plastics expand about four to ten times more than glass under heat,[5] visual distortion can

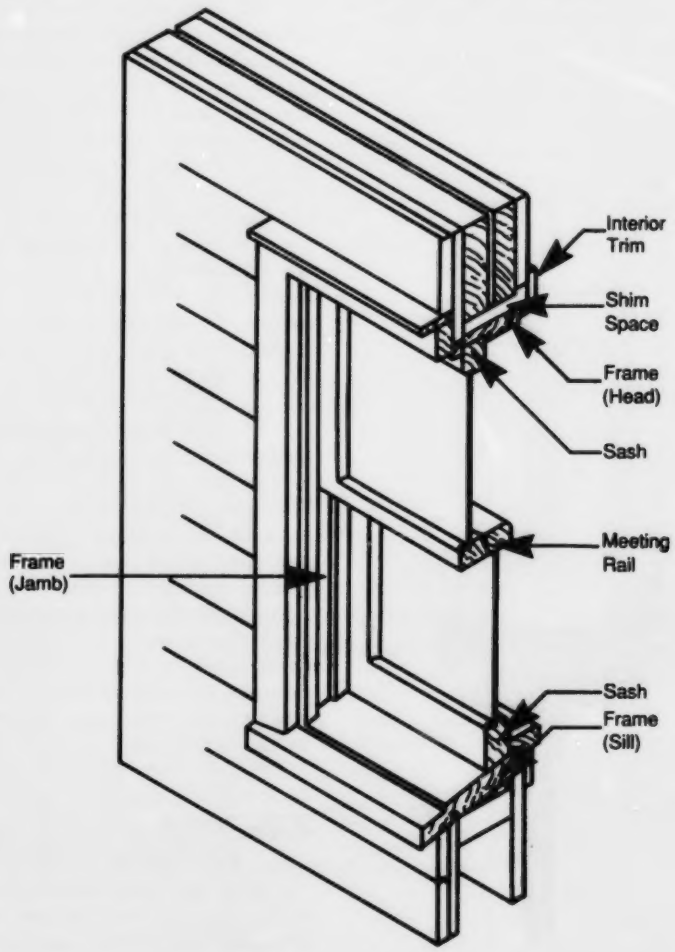


Figure 10. Components of a window.

result; therefore they are more suitable for applications which do not require perfect visibility. Proper detailing of the glazing and sash interface to accommodate thermal movement requires careful consideration.

Table 1 Initial light transmission

Glazing material	Visible light transmission (%)
PMMA (acrylic)	91–93
Polycarbonate	82–89
GRP	76–85
PVC	76–89
Soda-lime glass	88–90

Thin Films

Polyester and mylar films are used in the glazing industry to modify the properties of glass or to replace it. One application consists of applying a self-adhesive film directly on the inside surface of the inside pane; this is mostly done in retrofit of existing buildings to reduce glare and control solar heat gain and ultraviolet rays, which fade fabrics. The films are also used to create multiple air spaces within sealed glazing units; one glazing system on the market today consists of a sealed double glazing with a polyester film between two panes of glass, creating two air spaces without the weight of a third glass pane. These thin films are usually coated to modify the optical properties of the glazing unit, either to reflect solar heat back outside or internal radiating heat back inside, or to reduce the transmission of light or ultraviolet rays.

Glazing Unit

There are basically two ways of assembling multiple panes: they can be factory-sealed or unsealed. About thirty years ago, the first generation of factory-sealed multiple glazing appeared on the market. The technique has evolved from mechanical rigid connection of two panes of glass, which did not allow for differential movement of the panes, to 'soft' sealing of two separate panes, where sealants allow for some movement of the panes. New technology can bring forward new ways of sealing panes of glass.

Sealed Multiple Glazing

A factory-sealed multiple glazing unit, also known as 'insulating glass', is made of two or more panes of glass separated at the edges by a spacer(s) which contains a desiccant, and sealed at the perimeter with a single or dual seal (Figure 11). The edge spacer is usually rectangular, hollow aluminum or stainless steel, with a slit to allow communication between the cavity air and the desiccant. Its width depends on the desired width of the air space, usually between 12 and 20 mm. Recent developments in the field of edge spacers have brought forward new materials, such as fiberglass. The desiccant absorbs the moisture in the air trapped in the cavity at the time of manufacture, as well as any moisture that may slowly enter by diffusion during the service life of the glazing unit. The desiccant may be molecular sieve or silica gel. Manufacturers must select desiccants to avoid adsorption of nitrogen, which causes the air pressure in the cavity to drop, resulting in the deflection of the glass. This could reduce the thermal resistance of the air space at the center of the glazing, as well as cause a premature failure of the unit.

Polysulphide, butyl, silicone and polyurethane are commonly used sealants; they provide the structural bond as well as tightness against air, water and vapour flows. A proprietary system that has been on the market for a number of years, incorporates the edge spacer, the desiccant and the sealants all into one product. It consists of a butyl tape containing a metal strip spacer, which provides the rigidity.

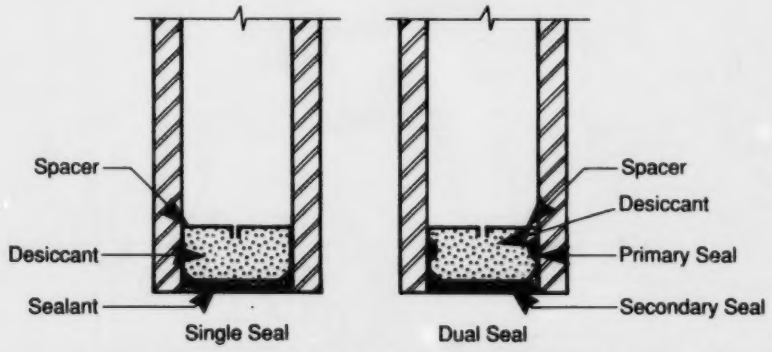


Figure 11. Factory–sealed double glazed unit.

The main advantages of factory-sealed multiple glazing are the absence of condensation between the panes of glass, the reduction from four to two surfaces to clean and the ability to incorporate high-tech options like coatings, films and gas-filled cavities to meet particular needs. On the other hand, the metallic spacer between the panes of glass represents a thermal bridge that cools the perimeter of the inside pane and makes it more prone to condensation than an unsealed glazing. As this is by design a 'closed system,' when it is exposed to temperature changes and wind pressures, the glass deflects and as a consequence, compression and tension of the sealants occur. In some cases, this leads to premature failure of the sealed glazing unit. Such premature failures can relate both to the unit and to the way it is installed. All users should ensure that the product they select meets the Canadian standard CAN2–12.8–M76 and preferably falls under the IGMAC (Insulated Glass Manufacturers Association of Canada) certification program.

Non-sealed double glazing

Non-sealed double glazing is available in two basic designs: the panes of glass can be fixed into the same sash or in separate sashes (Figures 12 and 13). The spacing between panes is about 20 mm in the former case and 75 to 100 mm in the latter case. For this design to work properly, there must be a good air seal on the inside sash to reduce air flow from the room into the cavity, otherwise excessive air leaks will cause condensation in the cavity. As a second line of defense, the cavity can be vented to the outside to equalize its pressure with the outside pressure. Then, if temperature or wind pressures cause air to move into or out of the cavity, most air exchange will be with outside air, which in winter is drier and less likely to condense.

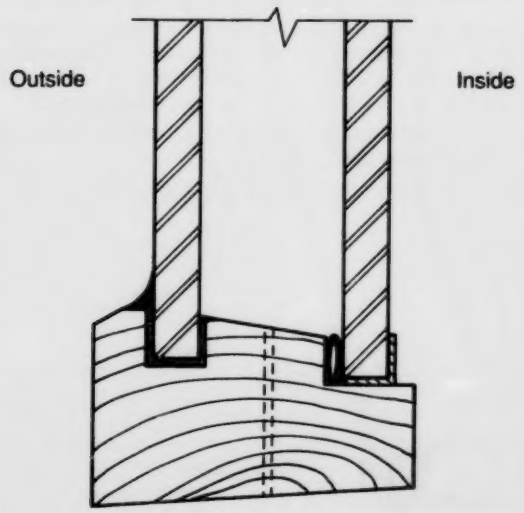


Figure 12. Unsealed double glazing in one sash.

The advantage of this system is that the unit does not have to be replaced because of condensation; it requires more frequent maintenance, such as cleaning of the cavity surfaces, and can last for a long time in that mode. A disadvantage is the limited options available to thermally improve such systems because a number of products used for thermal insulation are sensitive to moisture and pollutants and must be placed in a sealed unit. The availability of non-sealed double glazing is also limited; a few manufacturers make double glazing fixed in a single sash and even though many manufacturers make double glazing in separate sashes, it is usually available in the sliding models only.

Sash and Frame

Presently, sashes and frames are made of wood, aluminum, plastic and to a lesser extent, steel; fiberglass has been introduced recently. Each has advantages and disadvantages, which must be assessed according to the performance criteria selected for the needs of the owners or users. To provide improved systems, combinations of materials are commonly used to make up the final product.

Wood

Wood windows have long been a feature of our houses; a tradition is associated with them, especially in residential buildings. They are mostly restricted to houses and small buildings covered by Part 9 of the National Building Code, because of their combustibility

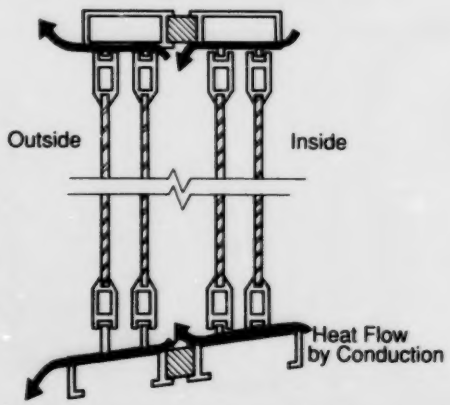


Figure 13. Indirect path of heat transfer in aluminum frame of unsealed window.

and frequent maintenance needs. The thermal resistance of wood is lower than that of insulation materials but used in windows it can provide a temperature on the inside face of the sash and frame higher than that of the glass, in a conventional unit. Wood used in windows is solid, so there is no air pocket where heat can be lost by convection, and the material itself has low thermal conductivity. A variety of wood species are used for window sashes and frames in Canada; most are soft woods like pine, cedar and redwood. Even though it is treated with a preservative after being cut to length, wood can be affected by moisture, which can make it warp or twist and may even induce rot if not controlled. The distortion of wood windows due to moisture absorption can make the operation of the window difficult. They require more time and effort to control moisture absorption and ultraviolet rays. They have to be painted or stained shortly after being installed and must be maintained every few years. It is important to control surface condensate because it promotes fungus growth and absorption of water by the wood can cause it to swell. To reduce the maintenance of wood windows, some manufacturers offer aluminum and plastic outside cladding. The aluminum cladding should not be in contact with the glass; otherwise, the edges are cooled significantly, increasing the potential for thermal breakage and inside surface condensation. Because those cladding materials are impermeable to moisture flow, there must be a vapour barrier (paint or varnish) on the three other surfaces of the wood to protect it against excessive moisture buildup at the outside face of the wood. Wood sashes and frames have stood the test of time and also benefit from ease of repair.

Aluminum

Aluminum windows are made of hollow extruded profiles assembled with mechanical fasteners. The profiles take a variety of shapes; a simple profile is illustrated in Figure 14. Because aluminum is highly heat conductive, a thermal break, usually made of plastic, is incorporated into the frame and the sash to reduce direct conductivity between the inside and outside parts of the window. This increases the temperature of the inside surface of the framing and somewhat reduces its potential for surface condensation. In some cases, pockets of air in the sash and the frame profiles are filled with sprayed foam or rigid insulation, which reduce the small heat losses due to air circulation within the cavities. Aluminum windows can be designed to meet structural requirements specific to the building; that makes them suitable for commercial and highrise buildings where wind loads may be appreciable; they are used in glass and metal curtain wall systems. They can be made in any colour, economics permitting, and require little maintenance but their durability can be affected by saline and polluted air.

The presence of a thermal break in the frame and sash is not sufficient to ensure adequate tolerance to the inside moisture level without condensation. For example, some models of windows used in commercial and residential buildings do not control 'indirect' heat conductivity (Figure 13); a sliding sash of unsealed double glazing still allows heat flow to bypass the thermally broken frame. Because the window framing is split into cold and warm parts, the thermal performance of the assembly depends greatly upon the detailing of the window. Questions like the following have to be examined to evaluate the design: Does the thermal

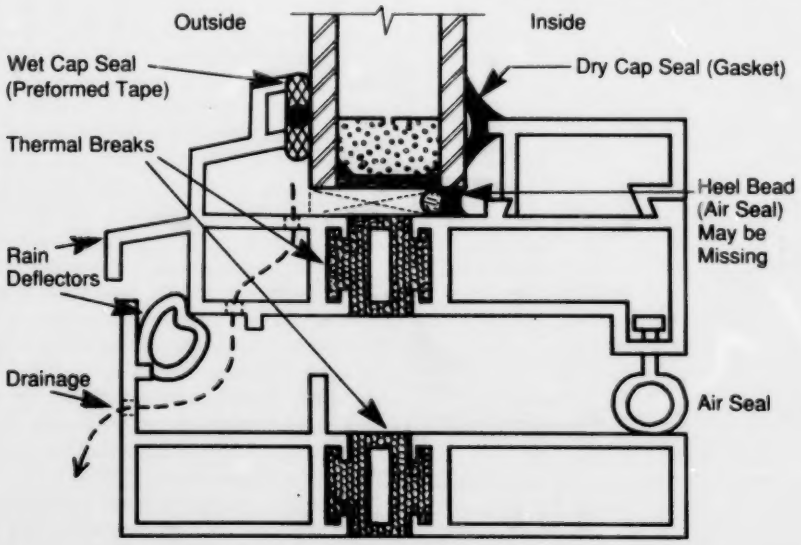


Figure 14. Cross-section of aluminum frame of inside awning window.

break in the frame align with that of the sash? Is the exposed area of aluminum on the warm side of the thermal break larger than that on the cold side? Is the glazing–sash joint made airtight with the outside or the inside part of the sash? Is the airtightness plane continuous over the whole window?

Poly(vinyl chloride) (PVC)

Poly(vinyl chloride) is the plastic used in windows; it is a thermoplastic, i.e., it can soften when heated and harden under cooling. PVC framing has a hollow profile making up many small air spaces (Figure 15). The joints between PVC parts are heat or solvent welded. The characteristics of PVC presently used in windows are difficult to define, since the additives play an important role in the properties of the end product and there have been many advances in material formulation. Additives can be plasticizers to reduce brittleness and improve processing, or stabilizers to protect against degradation caused by heat, oxidation and solar radiation. The thermal resistance of PVC is usually considered to be between that of wood and aluminum. To increase the rigidity of a large window sash, steel reinforcement is inserted within the sash profile; this steel component tends to cool down the surrounding PVC and increase its overall thermal conductivity. PVC windows are unlikely to require maintenance other than regular washing. They are stable in saline and polluted air. On the other hand, the high coefficient of thermal expansion (two to three times higher than aluminum)[6] has to be taken into account in the design and installation of the window. For example, in a cold climate, contraction of the window frame will enlarge the width of the joint with the wall; therefore careful selection of

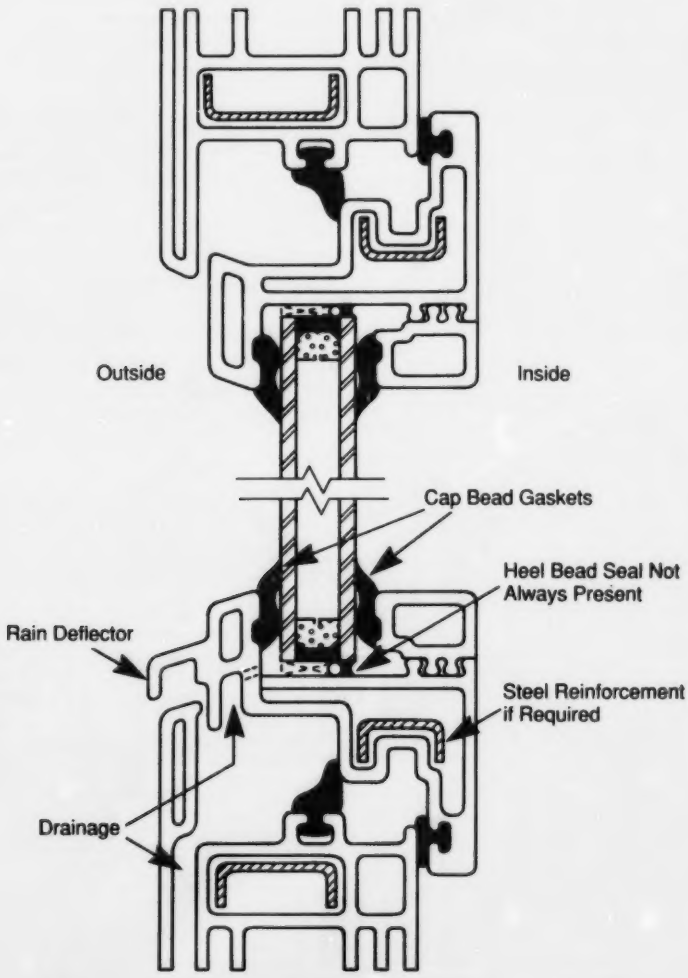


Figure 15. Vertical cross–section of PVC window (interior casement).

flexible sealants and joint width are important to avoid cohesive failure of the sealant. The possible fading of colours has historically restricted its selection to light tones, although new developments may have improved this feature. Because of plastic's high coefficient of expansion, dark colours on a southern exposure may cause excessive distortion. In case of damage, repairs are likely to require special skills.

Fibreglass

Fibreglass windows have been introduced on the market recently. They are made of 'pultruded' hollow profiles joined together mechanically. The use of fibreglass windows is so recent that its performance in service is still to be observed.

Combination of materials

Different materials can be combined to make window sashes and frames. For example, there are windows with vinyl sash and aluminum frame, or with a wood frame cladded with vinyl combined with an aluminum sash. The evaluation of performance is difficult because the interaction of these different properties cannot be predicted accurately. However if the advantages of each material are exploited, it can make for good performance.

Summary

Obviously windows are important features of buildings. Even though we all intuitively agree with that statement, not enough attention is paid to "making the most of it". What types, what size, what shape, what orientation, how much, how to do it, how to make sure, how to put it together, what is best, what design, what detailing, what not to do, what is innovative, what is proven: these are a sample of the multitude of questions that the building industry should be facing on every project. Are they actually faced? Too many decisions are still not supported by state-of-the-art technical knowledge of the windows and their implications. Problems can be avoided by a combination of understanding of design principles, design of buildable details, specifications relevant to the climate, good construction, proper testing at timely steps of the way, and feedback to the practitioners on the actual performance of the end product. Proper communication between the building team is also critical so that all parties reach a good understanding of what is being achieved and why. The purpose of the following papers is to contribute to the improvement of the building science and its transfer to the practitioners. Only in their hands can this make a difference.

References

1. "Windows." Canadian Standards Association, Rexdale, Ontario, CAN3–A440–M84, 19 p.
2. McLellan, G.W. and E.B. Shand, "Glass Engineering Handbook." McGraw–Hill, New York, 1984.
3. Schmidt, F.M., "The Window Book." Season-All Industries Inc, Pennsylvania, 1976.
4. "Improving the Energy Efficiency of Windows." Enerfacts, Energy, Mines and Resources, CEMR–173, 1984.
5. Blaga, A., "Plastics in glazing and lighting applications." National Research Council of Canada, Division of Building Research, Canadian Building Digest 213, 1980.
6. Beckett, H.E. and J.A. Godfrey, "Windows." Crosby Lockwood Staples in association with RIBA Publications Ltd., London, 1974.

Window Performance Factors

W.C. Brown and K. Ruberg

Introduction

The building envelope separates the controlled indoor environment from the uncontrolled outdoor environment. It protects the inhabitants from the elements, keeps noise and intruders out and controls heat loss and gain. Unlike opaque building components, windows transmit light. Unfortunately, they have lower resistance to heat flow and to sound transmission. Glass windows resist corrosion and weather well but they are less able to control fire propagation or to absorb impact than most common wall materials. In addition, they present problems for the architect who must devise details for joining the window to the wall.

Window performance factors include those that arise because of the light transmission properties of windows as well as those that are applicable to opaque walls. They can be divided into three major groups, as follows:

- windows as energy filters for the space
  - light transmission and access to view
  - thermal performance
  - sound transmission
- windows as part of the building envelope
  - structural strength
  - fire performance
  - airtightness and water penetration
- windows as a building component
  - operation and natural ventilation strategies
  - security
  - long term durability

Performance levels may be set by standards, or, if standards do not exist, they are implicitly decided by the building designer and specifier.

Standards, such as those produced by CSA[1] and CGSB,[2] can be used to specify minimum levels for performance requirements such as condensation potential, frame rigidity and sealed unit durability. Handbooks, such as those produced by the American Society of Heating, Refrigeration and Air Conditioning Engineers[3] and the Illuminating Engineering Society,[4] provide information on the heating and cooling loads produced by windows and on daylighting strategies. The National Building Code[5] and local codes based on it state minimum requirements for the size and location of windows with respect to fire safety. Finally, glass and window manufacturers are sources of information on the transmission and structural properties of their products.

The choice of windows for a building depends on the owner's or occupant's requirements, the architect's vision of the facade and form of the building, and the environmental demands to be met by the building envelope. A formidable array of issues, including those mandated by building codes, must be addressed when selecting windows.

The Window as an Energy Filter

Windows, as a transparent part of the building envelope, act as "energy filters". By changing the characteristics of the glazing, or the transparent portion of a window, different "types" of energy can be selectively transmitted or reflected.

A characteristic of radiant energy is its wavelength. The visible world, for example, is a reflection of the energy in the 400 to 760 nm (1 nm = 10^{-9} m) range. This coincides with the sun's peak power wavelengths. Ultraviolet wavelengths are shorter, and the heat we all radiate has longer wavelengths (around 10000 nm). Figure 1 illustrates this "spectrum" of energy, the peak wavelengths emitted by the sun and by people.[6]

Clear glass transmits most of the solar radiation, or short wavelength energy, falling on it. This property of glass allows us to see through it and to use the light from the sun to illuminate tasks. The energy gain from the sun can also provide heat to a room.

On the other hand, clear glass absorbs most of the infrared radiation (long wave radiation) emitted by people and interior building surfaces. However, most glazing materials are poor thermal insulators and the absorbed energy is readily conducted to the cold exterior winter world. As a consequence, windows tend to have high transmission in relation to insulated walls.

Noise is also a frequency dependent phenomenom. Windows can transmit noise by mechanical vibration and through air leaks associated with the window.

By properly specifying the wavelengths glazing should reflect, transmit and absorb, windows can decrease operating costs for lighting and heating and increase the visual comfort of building occupants. Proper selection can also optimize the thermal and aural performance of windows.

Light and View

Historically, the primary function of a window has been to provide the building occupants with light and view. All other performance factors must be balanced against these primary reasons for installing windows in a building.

Transmission characteristics of glazing

The part of the electro-magnetic field our eyes are sensitive to lies between 400 and 760 nm. This constitutes "light". Clear glass transmits most of the visible radiation falling on its surface while absorbing or reflecting the rest (Figure 2). Heavily tinted and reflective glazings transmit as little as 8%. Both the amount of natural light available in a room, and its colour, can be affected by the choice of glazing. Impurities and thickness both increase the absorption of light by glass. Table 1 provides [illegible] of light transmission values for various glazing materials.

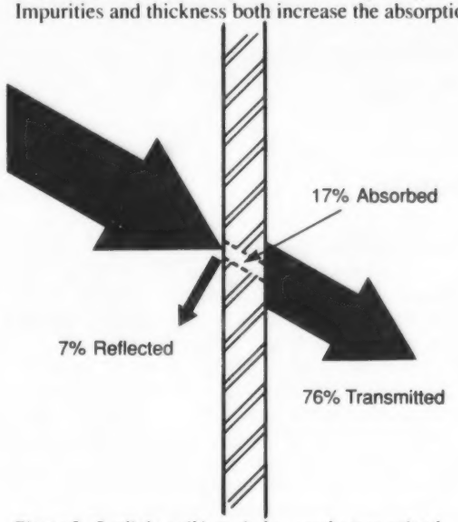


Figure 2. Sunlight striking window can be transmitted, reflected or absorbed.

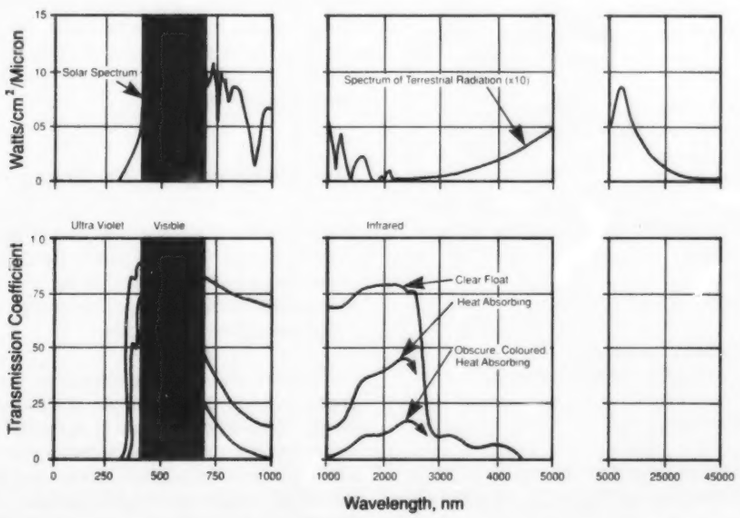


Figure 1. Solar radiation and spectral transmittance for typical architectural glass.

About 3% of the sun's energy reaching the earth's surface is found in the ultraviolet (UV) region of the spectrum.[7] Clear glass transmits [illegible] of the incident ultraviolet energy. Plastic glazing materials transmit anywhere from [illegible] of this energy, while glazings that transmit a large portion of the UV energy, e.g. very pure silica glass, are useful in health care settings where the antibacterial and [illegible] effects of UV are desired.[8] On the other hand, exposure for plastic finishes, paints and fabrics will [illegible] under UV exposure. Even diffuse solar radiation will [illegible] UV and ultimately cause fading in coloured fabrics and artwork.

Table 1 Light transmission characteristics

Description	Visible
Float, single strength clear glass double strength clear glass	91% 90%
Float, clear – 2.35 mm thick 6.35 mm thick 19.05 mm thick	91% 89% 83%
Float, clear mirror tinted blue-green tinted bronze	89% 75% 28%
Double glazed, clear tinted or mirrored (depending on tint)	80% 10–35%

About half of the sun's energy is found in the near infrared (shortwave) region of the solar spectrum. Clear glass transmits 80% to 90% of this radiation. It must be selectively absorbed or reflected if solar heat gain is to be reduced. Clear glass absorbs 80% to 90% of the far infrared (long wave) radiation emitted by bodies at terrestrial temperatures, but re-emits the heat at the same rate.

Daylighting

Daylighting is the use of natural light to illuminate tasks [illegible] advantage electric lighting and cooling loads in [illegible] buildings if the fenestration and the [illegible] properly designed, and if the lighting controls [illegible] an integral part of the daylight system.

[illegible] generally improves seeing the [illegible] brightness, or glare, can cause a reduction [illegible] and contrast sensitivity. Glare results from the presence of excessively high brightness sources, such as windows, in the visual field. Glare from windows can be reduced by reducing the view of the sky through the use of vegetation or overhangs and by spreading the light further into the interior of the building. Increased use of video monitors has led to more occurrences of disability glare, resulting from a high intensity light source and low-luminance surroundings. Flat screens with anti-reflection coatings can almost completely eliminate this problem (Figure 3).

The colour rendition of furniture, fabrics and tasks is affected by tinted glazing. For example, reduction of solar gain achieved through the use of yellow tinted

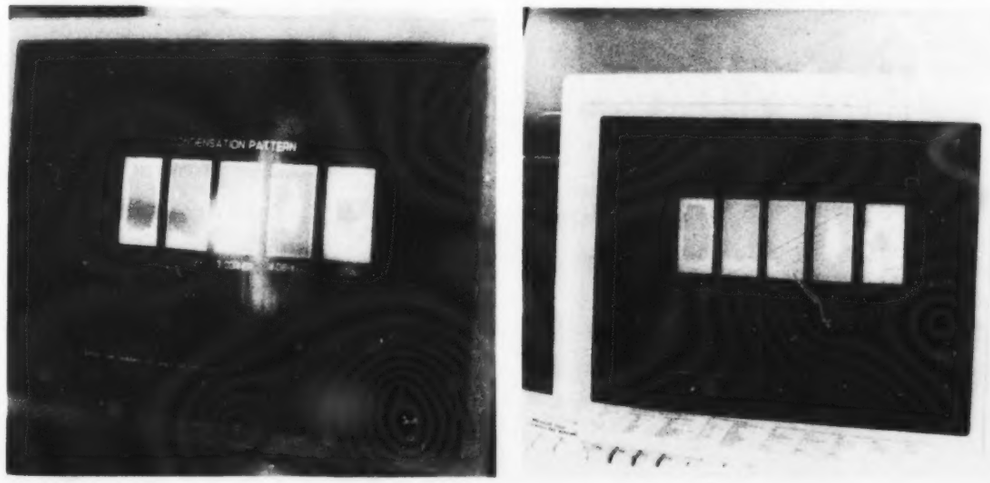


Figure 3. Flat screen with anti-reflection coating eliminates glare.

plastic films casts a yellow pallor on the inhabitants and the tasks. But, if gold tints are used on a window, there is a resultant loss of the yellowish part of the spectrum on the colours inside the building.

An example of facade design that successfully supports daylighting features is the Lockheed Building in San Francisco where the skylights, interior ceiling design, and window placement combine to provide relatively glare-free natural lighting. Figure 4 illustrates a cross-section of the building and the clerestories with light shelves that allow light to penetrate into the space[9]. Dimming controls reduce peak power consumption in this building by 60% with a simple payback in 2.6 years.

View

Although the benefits are not easily measured, or even well understood, view is a coveted feature and will add to the value of a property in both the residential and commercial real-estate market. In Norway, access to view and daylight are mandated by the labour code. View often takes precedence over the thermal considerations of window size and placement during the design of buildings. Reflective coatings and tinted glazing can affect the visual perception of the outside scene and the architectural quality of the glazing. For example, very reflective or dark-tinted glazing will cause the outside to appear cloudy even on the sunniest day.

Daylight and view combined can lead to pleasant interior spaces. On the other hand, indiscriminate use of windows can lead to uncomfortable conditions and special solutions may be required to reduce the complaints generated by occupants.

Aesthetics

Architectural facade design trends have experienced radical changes during the 20th century as glass technology provided designers with larger sheets of vision glass. These advantages were applied first to exhibition buildings, and then in the commercial sector. The adoption of the Bauhaus aesthetic by North American architects in the 1950s has evolved into the glass curtain wall design on most commercial buildings today.

As deconstructivistic, postmodernistic, rationalistic, brutalistic and free form architectural facade strategies vie for domination of the architectural design world, new glass finishes, shapes and mountings are required to allow these concepts to become real. Structural glazing, mirrored finishes and curved glazing have all provided the architect with aesthetic freedom in facade design.

Mirrored glazings have also led to infinitely re-reflecting corridors in our downtown cores. A view of downtown Ottawa is shown in Figure 5. Tom Wolfe has strongly criticized the excessive use of these "simple"

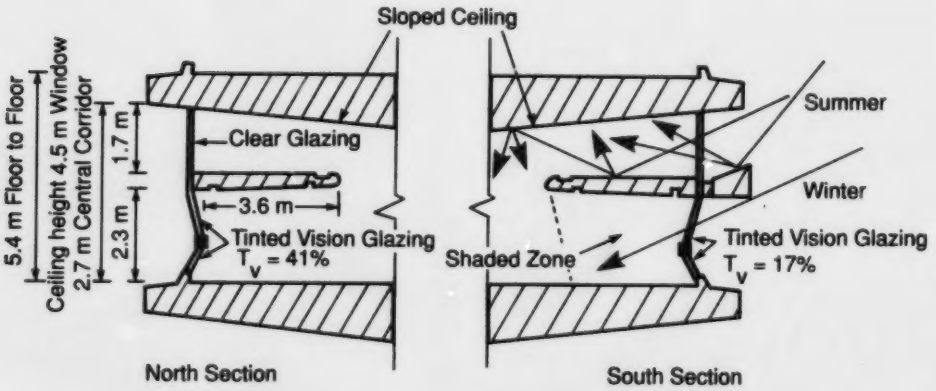


Figure 4. Light shelves and canted, light-coloured ceilings distribute natural light to work surfaces.

facades applied to box-like forms, and attributes them to the acceptance of the Bauhaus aesthetic in North America.[10]

Thermal Performance

After light and view, the most commonly used performance criteria of windows is thermal performance. It involves both heat transmission through the window and surface temperature of the window. Heat transmission includes heat loss from the heated interior to the colder exterior and heat gain by solar radiation. Surface temperature performance relates to moisture condensation and its effect on the durability of the system. Both aspects of thermal performance can have an impact on the thermal comfort of the space.

Heat transmission

Heat is transferred from high temperature areas to low temperature areas by conduction, convection and radiation. All three mechanisms of heat transfer are important to the thermal performance of windows. Figure 6 illustrates the mechanisms for heat transfer through a window.

Thermal transmittance, or U-value, is normally used to rate the heat transmission of windows. The amount of heat transferred through a window is directly proportional to the U-value of the window. U-value does not include heat transferred by air leakage or solar radiation. Overall thermal resistance, the reciprocal of U-value, is the arithmetic sum of the thermal resistance of the window, both glazing and frame, plus the surface resistances on the inside and outside of the window.

Most glazing materials, in the thicknesses used for windows, have very low thermal resistance (<0.02 $m^2 \cdot K/W$). However, the thermal resistance of the glazing system can be increased significantly by enclosing one or more air spaces between panes of glass. For example, the thermal resistance of a 13 mm air space enclosed between two panes of clear glass is about 0.21 $m^2 \cdot K/W$. Heat transfer across the space will be by a combination of conduction, convection and radiation. Convection will not be significant in air spaces less than about 15 mm thick, but it becomes important as the thickness of the air space and the temperature difference across the air space increases. The optimum thickness for air-filled multiple clear glazing is between 12 and 25 mm.[11] Heat transfer by conduction and convection can be reduced if low conductivity, high viscosity gases are used to fill the space; heat transfer by radiation can be reduced if low emissivity coatings are applied to one or both glass surfaces. The benefits to be obtained from these changes are discussed in the fifth paper, *New Technologies in the Window Industry*.

Heat transfer through the window frame is generally by conduction. The proportion of the overall window heat transfer that passes through the frame will depend on the relative areas of frame and glazing and on the materials used in the frame. Wood frames are good thermal insulators. Frames constructed of aluminum and other low resistance materials must be designed with a higher resistance material separating the inner section of the frame from the outer section (known as a thermal break) in order to provide acceptable performance.

Figure 5. Downtown Ottawa.

Heat is transferred between a window and its surroundings, whether inside or outside, by convection and radiation. The resistance to heat transfer of these two mechanisms acting in parallel is called the surface resistance. Its value will depend on the speed of the air flowing past the window and on the emissivity of the window surface. Under still air conditions it can vary between 0.10 m^2•K/W and 0.38 m^2•K/W depending on the emissivity of the glazing surface and the temperature difference between the glazing and surroundings.[12] A value of 0.12 m^2•K/W is generally accepted for vertical clear glass under winter conditions for design purposes. This makes up about one third of the overall resistance attributed to a double glazed window.

Solar gain through a window can offset some or all of the heat loss through the window.[13] South-facing double glazing below 50°N latitude can have a net heat gain over the heating season. At more northerly latitudes, the solar gain will not be sufficient to offset the loss through clear glass windows. Use of low emissivity glazings increases this range. Passive solar gain can be best utilized in residences where temperature control is less critical and where the largest load during the winter is space heating.

Of the many passive solar buildings that have been constructed, the most successful strategy has proved to be "direct gain". In this strategy, most of the building's windows are oriented south. However, it has been shown that the area of south-facing glazing should be limited to 15% of the floor area in order to limit overheating.

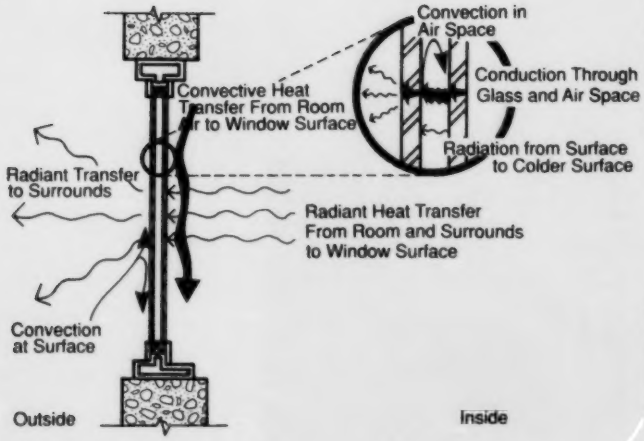

Convection in Air Space
Conduction Through Glass and Air Space
Convective Heat Transfer From Room Air to Window Surface
Radiation from Surface to Colder Surface
Radiant Transfer to Surrounds
Radiant Heat Transfer From Room and Surrounds to Window Surface
Convection at Surface
Outside
Inside

Figure 6. Window heat loss mechanisms.

Surface temperature

Condensation on windows is a common complaint from occupants. It occurs when inside surface temperatures are lower than the dew point temperature of the air adjacent to the surface. Windows are prone to cold inside surface temperatures because the thermal resistance of glazing systems is typically lower than the inside surface resistance.

Surface temperature performance of a glazing system can be improved in a number of ways. The thermal resistance of the glazing system can be increased by the use of multiple air spaces, by the use of low emissivity coatings, or the use of low conductivity gases in the spaces between lights. The inside surface resistance can be reduced by locating the inner light close to the inside surface of the wall. It can also be decreased by blowing air directly against the glazing surface. Special coatings that absorb solar radiation will also increase the inside surface temperature on days when the sun shines. The latter two options should be used with discretion since they will increase the potential for thermal breakage.

Surface temperature performance of the frame can be improved by constructing the frame with low conductivity materials or by using thermal breaks between inside and outside frame surfaces. Constructing the sash or frame with a greater exposed area on the inside than on the outside will also improve surface temperature performance.[14] In extreme cases, supplemental heat, for example from a heating wire, can be used to selectively supply heat to the frame and thereby reduce the potential for condensation. This is a technique that can be considered as a retrofit solution for problems produced, for example, by a change in occupancy or operating conditions.

Thermal comfort

Thermal comfort of a space is affected by the presence of large cold surfaces such as windows in winter. They can contribute to occupant discomfort through direct radiant heat from the occupant to the surface and through uncomfortable cold air drafts flowing off the surface. Window treatments, such as curtains or drapes, can reduce the effect of the cold radiant surface. However, in most cases the building's heating system is expected to overcome these potentially uncomfortable conditions.

The temperature of a space can also become uncomfortably warm due to direct solar radiant gain. Spaces with large south-facing glazed areas can be pleasant in January and February but uncomfortably hot for the rest of the year, particularly in spring and fall. Similarly, horizontal and west facing glazing lead to overheating in summer with significantly increased cooling loads. Any of these situations can put an extra load on the building's air-conditioning system and reduce the thermal comfort of the occupants.

Sound Transmission

Sound transmission through windows is governed by the mass and stiffness of the window, the same physical principles that affect sound transmission through walls. However, practical noise control measures are limited by the properties of glass and other glazing materials and the characteristics of window assemblies.[15,16] Since sound is an air-borne phenomenon, noise control measures can also be strongly affected by the airtightness of the window.

Sound is composed of many frequencies. Sound transmission loss is a standardized measure of noise reduction for specific frequency ranges. Sound transmission class (STC), which is the single figure rating of sound transmission most commonly used in North America, is calculated by fitting a standard contour to the transmission loss data. Although the STC rating of building elements is generally satisfactory for ranking their reduction of noise from sources such as the human voice, it does not properly rate insulation against sources with strong low frequency content such as aircraft and road traffic.[17]

For insulation against outdoor noise, STC values in the range of 30 to 45 are generally required for windows. Provincial regulations and Canada Mortgage and Housing Corporation guidelines provide methods for determining the appropriate value.[18] Another method is provided in a publication from IRC.[19]

The STC rating of typical double glazing (4 mm glass with 13 mm air space) mounted in a wood frame is about 33. Increasing the glass or air space thickness will give higher STC ratings (see Table 2).[20] For each doubling of air space thickness, the STC increases by approximately 3. However, if the air space thickness is less than 10 mm, the STC rating is not significantly different from that for a single layer of the same glass. Double or triple glazing of similar total thickness provides similar STC ratings unless the thickness of both spaces of the triple unit is greater than 25 mm. Using different glass thicknesses for multiple glazing units improves the STC rating. For example, double glazing with 3 mm and 6 mm lights of glass will have an equal or higher STC rating than one with two 6 mm lights of glass. A ratio in glass thickness of about 2 to 1 is most effective.

Transmission of sound energy through the window frame can limit the noise reduction. Tests have shown that, for glass mounted in wood sashes supported in a wood frame 40 mm thick, transmission through the frame is insignificant. Some tests with lightweight metal frames have given lower STC ratings, apparently due to vibrations transmitted by the window frame. When a very high STC rating is required, using separate glazing units mounted in structurally independent walls will eliminate the problem of transmission through the frame.

Sound transmission through cracks in and around windows reduces their effective STC rating. For example, the STC of an operable window, even one with good weatherstripping, is usually from 3 to 5 lower than that for an equivalent fixed window.

The Window as Part of the Building Envelope

Glazing is becoming the predominant element in the walls of most commercial buildings, often accounting for 90% of the area. Windows must be able to withstand the structural stresses imposed on the building envelope of which it is a part. In addition, the performance of windows under fire conditions must be recognized when designing windows for buildings. Local building codes prescribe the standards that apply to window performance in fires. Finally, windows must also function as the air, vapour and weather barriers of the building.

Structural Performance

The structural performance of glazing requires that the strength of the material be adequate to resist the

Table 2 Sound reduction

Glass thickness (mm) No. 1	Glass thickness (mm) No. 2	Air space (mm)	STC rating
3	n/a	n/a	29
6	6	12	29
12	6	50	39
12	6	102	40
12	6	152	42
19	10	152	40
12	6	152	44
5	8	102	39
25	6	152	40

stresses imposed on the material. These stresses result from environmental factors, such as wind, temperature and barometric pressure, and from physical factors, such as glazing details and deformation of support systems.

Strength of glass

Soda-lime glass is normally used for windows. Annealed float glass is the most widely used and least expensive. Heat-strengthened glass can have twice the strength of annealed glass. Tempered glass, which can have twice the strength of heat-strengthened glass, is often used where safety glass is required. While most glass breaks into large pieces, fully tempered glass produces small cubic pieces when it shatters.[21] On rare occasions tempered glass suffers spontaneous breakage, apparently because of microscopic inclusions in the glass.

Glass is a brittle material and the structural failure of glass can be quite sudden and dangerous. While the theoretical strength of glass is quite high in both tension and compression, this strength is not achieved in practice because of surface and edge flaws in the glass sheet. Microcracks found throughout the surface act as stress concentrators and reduce the useable tensile strength considerably.[22] Because the effect of these stress concentrators increases as the glass ages, old glass is generally weaker than new glass.

The dependence of glass strength on surface flaws, which vary randomly in severity and location, causes the breaking stress of samples of glass from the same batch to vary randomly as well. Breaking stress is thus not a single number but can be summarized by a mean value and a measure of its variability about the mean. The relative variability is given by the standard deviation divided by the mean, i.e. the coefficient of variation. The coefficient of variation for the breaking stress of annealed glass is generally about 20% to 25%; it is usually less for heat strengthened and tempered glass. Since the probability of a flaw increases with the area of the glass, the mean breaking stress tends to decrease as the area of the glass increases.

It is common in the structural design of glass to specify a probability of breakage of 0.8% (8 in 1000) at the design load determined for the installation. Since the design load also has a statistical probability of occurring during the life of the building, the chance of breakage in one year is usually about 10 times less than the specified probability of breakage. However, the expected lifetime of the glazing should also be considered in the structural design. The longer the expected lifetime for the cladding, the lower the specified breakage probability must be.

When glass must resist more than wind loads, special engineering design considerations must be brought to bear. Laminated glass is typically used in applications such as security cages or aquariums where increased impact resistance or toughness is required. For sloped glazing and skylights, a laminated or wired inner light is often used to prevent broken shards from falling on the occupants if breakage occurs.

Stresses on the glass and frame

Tall buildings, particularly those with irregular shapes, are subjected to complex wind pressures at building corners and along the faces. Wind tunnel tests are the most reliable method of determining the pressure variation on the facade of commercial buildings for design purposes. Simplified methods for calculating wind pressures on cladding (glass) are provided in the Supplement to the National Building Code.[23]

In contracts for commercial structures, it is normally the responsibility of the architect to specify the wind loads for cladding design. The area and aspect ratio of the glazing are also required for the structural analysis. Finally, acceptable breakage probabilities must be specified if a glass strength analysis is to be performed by the bidder, and if an optimum thickness for the glazing is to be determined.

Thermal stresses, leading to thermal breakage, are another source of concern in the design of glazing systems. They are caused by a difference of temperature between the edges and middle of a light. The condition of the edge of the glass pane will strongly influence the breaking stress of the pane. To reduce the potential for thermal breakage, the following situations should be avoided:

- low thermal resistance connections to heat sinks such as masonry which can cool the edge of the glazing,
- deep reveals that cast shadows along the edge and allow solar gain on the middle of the glazing,
- reflective coatings facing the air space of a double glazed unit or an inner light of heat absorbing glass,
- air-conditioning units blowing air directly on the glazing.

Poor glazing details can also lead to structural failure of the glazing. For example, the glass can fracture if building movement or thermal expansion of the glass causes glass–to–metal contact. Problems with glazing details can usually be avoided by following the manufacturer's glazing recommendations.

Current practice for the structural design of glazing varies with the designer. A new standard on structural

design of glass is presently in the final stages of development.[24] When adopted, it should clarify glazing design and specification.

Fire Performance

Most glazing materials, including glass, do not withstand the heat and pressures produced by a fire. Plastic glazing materials can contribute to the fire loading of a space. Once a window is broken, fire can spread up the exterior wall and to adjacent property. On the other hand, glazed openings are frequently used to meet building code requirements for emergency exits and for access to a building by fire fighters.

Windows as fire rated partitions

The use of glazing in fire separation is severely restricted by building codes, including the National Building Code. Ordinary window panes shatter after only a few minutes' exposure to fire, due to thermal stresses caused by large temperature differences across the glass and between the edges and the mid-zone of the pane.[25] The glass will experience positive pressure, due to the expansion of fire gases in the fire compartment, blowing the glass out of the frame.

The traditional method of using glazing in fire-resistant construction has been to divide the panes into small sections and to reinforce the glass with wire which will hold broken fragments in place. Wired glass can be used in doors required to have a 2 hour fire rating (NBC 3.1.6.11) provided the amount of glazing is limited to 645 cm^2. The National Building Code also allows twice as much window area in exterior walls close to adjacent buildings if the windows are glazed with wire glass or glass blocks (NBC 9.10.14.4).

Code requirements for egress

In residential construction, the National Building Code requires provisions for emergency exit from bedrooms. Bedrooms without a door leading to the exterior must have at least one window with an unobstructed opening not less than 380 mm in height, 380 mm in width and 0.35 m^2 in area (NBC 9.7.1.3).

In small multi-family residential buildings, the National Building Code requires "openable panels" for firefighting purposes on the ground level and on the third floor in at least one wall facing the street. These access panels must be 1.1 m high by 0.55 m wide and be easily openable unless they are glazed with plain glass (NBC 9.10.19.1). In large buildings, these panels must be located at 15 m intervals along the facade facing the street (NBC 3.2.5.1).

These excerpts are from the 1985 edition of the National Building Code of Canada. The requirements may be somewhat different in provincial and local codes based on the NBC. However, they are representative of constraints imposed by building codes.

Airtightness and Water Penetration

As part of the building envelope, windows must control vapour and air penetration from the interior and wind and water penetration from the exterior. The glazing system is one place where the vapour barrier, air barrier and weather barrier become one. While the basic concepts associated with these barriers are presented here, the issues of proper detailing and installation of windows are addressed in the fourth paper, *Integrating the window with the building envelope*.

Vapour diffusion and air leakage control

Moisture in the form of vapour can move from the warm moist interior to the cold dry exterior by vapour diffusion and by air leakage. These are two distinct mechanisms of moisture transfer and they each require their own control system. Although air leakage is considered the more important mechanism of moisture transfer, both can lead to condensation with associated durability problems. Air leakage can also contribute to excess heat loss and poor noise control.

Vapour diffusion is driven by vapour pressure differences through holes and vapour permeable materials. The vapour pressure difference arises because of the difference in humidity levels between the moist interior and comparatively dry exterior. Although all building materials have some resistance to vapour diffusion, a 'vapour barrier' (i.e. a material with a vapour permeance below a standard level) is normally installed to control moisture movement by vapour diffusion.

Air leakage is driven by air pressure differences through holes and air permeable materials. The air pressure difference can be generated by stack effect, wind, and mechanical ventilation systems. Air leakage must be controlled by an air barrier system. The requirements for an air barrier system are low air-permeable materials in combination with leak-free joints and the ability to withstand the forces induced by air pressure differences.

Glass and most glazing materials perform quite adequately as both vapour and air barrier materials. The CSA standard on windows, CAN3–A440–M84, prescribes procedures for measuring, and rating, the airtightness of windows as a building component. Window joints must be designed and built so that the integrity of the moisture control systems is not compromised.

The window as a weather barrier

Water and snow penetration of the building envelope is caused by gravity and wind-induced pressure differences. Glazing materials are not permeable to water and CSA A440 prescribes procedures for measuring water penetration of windows as a building component.

As with vapour diffusion and air leakage control, the joints are the potentially weak areas where penetration occurs. The window must be integrated with the building envelope weather barrier in order to ensure proper performance. In addition, a provision must be made in the design of the window for drainage of any water that does get past the weather barrier.

The Window as an Operable Building Component

Once installed, the window must conform to expected operating modes and must be maintained. Operation of the window depends on its use in the building. Commercial buildings in North America have evolved to almost universal use of fixed and sealed envelopes with ventilation and cooling provided by mechanical HVAC systems. Almost all residential buildings, on the other hand, have operable windows since mechanical ventilation and cooling is less common in these buildings.

Operation of Windows

The use of windows for ventilation and summer cooling is common in Canada. As with daylighting, it is the location of the window and the shape of the room, among other things, that determine the potential for natural ventilation. The type of operable window specified depends on the aesthetic, egress and ventilation requirements in the space. Operable windows come in many forms, from crank operated casements, through hoppers and awnings, to vertical and horizontal sliders.

Ease of operation

For a window to be useful as a ventilation device and as a means of egress, the force required to operate the window should be such that it is operable by a majority of the population. Ease of operation is particularly important for disabled or elderly people.

In a limited study performed by the University of Ottawa, it was shown that physically disabled and non-disabled people could exert about the same force on the roto-operator of a casement window. However, disabled subjects could exert only 20% as much force on a vertical slider as non-disabled subjects. The time required to open casement and slider windows was also measured. While it was shown that disabled subjects took longer to open the windows, the difference was not considered sufficient to create problems in emergency situations.[26]

A study conducted by the Building Research Establishment in the UK showed that the height of the operator handle above the floor was important when maximum effort was required. In these circumstances, the optimum height was between 1.0 and 1.6 m, depending on the type of operator being used. The study also found that the force that could be exerted was influenced by the size and shape of the operator handle.[27]

Natural ventilation

Operable windows provide the potential for both cooling and natural ventilation. Window openings allow outside air to move through interior spaces carrying away heat and unpleasant odours. (By the same token, open windows may let exterior odours in.) The location of the building with respect to the site, the building shape, the shape of the interconnected spaces, the

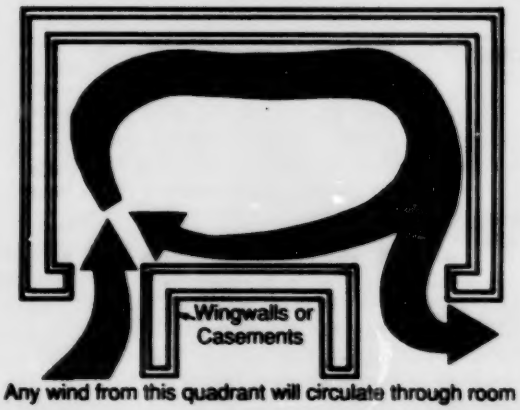


Figure 7. Window positioned in room to provide maximum ventilation.

window shape, size and placement all influence the amount of air that passes through the rooms. "Through ventilation", i.e. from openings on the windward side to openings on the leeward side, is the more common form of ventilation obtained with windows. Wingwalls (Figure 7) can increase the ventilation potential of a single room with two windows.[28]

Security

Windows must be secured against accidental breakage in high-traffic areas as well as against forced entry. In the first case, the National Building Code provisions for tempered glass used in high risk areas minimize danger to occupants. Glass should be visibly marked if it is placed in areas where occupants might walk into it. Laminated glass should be used in applications such as skylights where falling fragments present a risk.

Security against forced entry is achieved by considering the glazing, frame and hardware. Typically, thieves will avoid breaking glass to gain entry.[29] The window hardware (hinges, locks, etc.) should be on the interior or in the frame and should not be removeable from the outside with simple implements. Locks on sliding mechanisms should be such that they cannot be opened by rocking the sash. Other types of security devices may be incorporated into the window design. For example, wire laminated into the glazing may be tied to a security system. Steel bars set into masonry can provide further protection against forced entry, but prevent the use of the window as an emergency exit.

Extra security can be provided by laminated glass. Bullet proof glass is 12 to 50 mm thick, depending on the type of projectile it has been designed to stop. Security glazing requires deeper rabbets to hold shattered glass in place. Plastics, such as polycarbonates and acrylics, have 25 to 30 times the impact resistance of glass and should be considered where impact resistance is important. However, their scratch resistance and weatherability are not as good as glass, and their cost is higher.[30]

Durability

As with all building envelope components, the long-term durability of windows is a function of the environmental forces acting on windows and the materials from which they are constructed. However, unlike opaque building components, deterioration of the surface of glazing will affect performance as well as appearance. Proper maintenance of the glazing and frame will contribute to longer life of the window. In this regard, provision for washing windows should be considered when designing the facade of high rise buildings. It can be an expensive proposition to add this feature after the facade has been designed, especially if the facade has a complicated, multi-dimensional form.

Performance Checklist

Windows are complex building envelope components. Their selection by architects and designers is dependent on the occupant's needs and the building's environment. Improved performance in one category might lead to compromises in another. It is this conscious trade-off of features that should be recognized when specifying windows for a building.

Many aspects of window performance are not covered by performance standards. However, as standards for measuring window performance continue to evolve, the need for subjective evaluation of performance criteria diminishes. CSA A440 and the proposed CGSB 12.20–M standards are designed to help in the specification of the performance requirements of windows.

Finally, with so many options available for glazing and framing, choosing a window requires matching performance against cost. A specific window will perform some of its duties better than others. The challenge is to match performance requirements with available window technology and remain within budget. Criteria listed in this paper provide a checklist for the designer. Standards and the designer's budgetary constraints must be balanced with the desired performance levels.

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References

1. "Windows." Canadian Standards Association, Rexdale, Ontario, CAN3–A440–M84, 1984.
2. "Insulating Glass Units." Canadian General Standards Board, CAN2–12.8–M76, 1976, 15 p.
3. "Handbook of Fundamentals." American Society of Heating, Refrigeration and Air Conditioning Engineers, Atlanta, Georgia, 1985.
4. "Recommended Practices of Daylighting." Illuminating Engineering Society of North America, New York, RP–5–79, 1979, 50 p.

5. "National Building Code of Canada." Associate Committee on the National Building Code, National Research Council of Canada, NRCC 23174, 1985.
6. Garden, G.K., "Characteristics of Window Glass." Division of Building Research, National Research Council of Canada, Canadian Building Digest 60, 1968, 4 p.
7. Shand, E.B., "Glass Engineering Handbook." McGraw Hill, New York, 1958, p. 65.
8. Hopkinson, R.G., P. Petherbridge, and J. Longmore, "Daylighting." Heinemann, London, 1966, p. 8–9.
9. Benton, C., M. Warren and S. Selkowitz, "Lighting System Performance in an Innovative Daylighted Structure: An Instrumented Study." 2nd International Daylighting Conference, Long Beach, 1986. Lawrence Berkeley Laboratories, Berkeley, California, in press.
10. Wolfe, Tom, "From Bauhaus to one house." Washington Square Press, New York, 1982, 128 p.
11. Solvason, K.R. and A.G. Wilson, "Factory-sealed double-glazing units." Division of Building Research, National Research Council of Canada, Canadian Building Digest 46, 1963, 4 p.
12. "Handbook of Fundamentals." American Society of Heating, Refrigeration and Air Conditioning Engineers, Atlanta, Georgia, 1985.
13. Barakat, S.A., "Solar heat gain through windows in Canada." Division of Building Research, National Research Council of Canada, NRCC 18674, 1980.
14. Wilson, A.G., "Condensation on inside window surfaces." Division of Building Research, National Research Council of Canada, Canadian Building Digest 4, 1960, 4 p.
15. Quirt, J.D., "Sound insulation characteristics of windows." Division of Building Research, National Research Council of Canada, Canadian Building Digest 240, 1985, 4 p.
16. "Noise control in buildings." Proceedings of Building Science Insight '85, Institute for Research in Construction, National Research Council of Canada, NRCC 27844, 1987, 60 p.
17. "Standard classification for determination of sound transmission class." American Society for Testing and Materials, Philadelphia, PA, Standard E 413–73, 1987, 3 p.
18. "Road and rail noise: Effects on housing" and "New housing and airport noise." Canada mortgage and housing corporation, NHA 5156 and NHA 5185, 1981.
19. Quirt, J.D., "Controlling sound transmission into buildings." Division of Building Research, National Research Council of Canada, Building Practice Note 56, 1985, 34 p.
20. "Window selection guide." American Architectural Manufacturers Association.
21. Wassermuhl, S., "A guide to vision glazing." The Canadian Architect, November 1987, pp. 48–50.
22. Bowes, W.H., L.T. Russell, and G.T. Suter, "Mechanics of engineering materials." John Wiley and Sons, New York, 1984, p. 579.
23. "Supplement to the National Building Code of Canada." Associate Committee on the National Building Code, National Research Council of Canada, NRCC 23178, 1985.
24. "Structural design of glass for buildings." Canadian General Standards Board, Ottawa, Ontario, Draft Standard 12.20–M, 1988.
25. Kim, A.K., "Fire exposure of glazing." Proceedings Fourth Conference on Building Science and Technology, University of Waterloo, Waterloo, Ontario, 1988, pp. 14–27.
26. Yung, D. and I. Oleszkiewicz, "Fire spread via exterior walls of buildings." Proceedings Fourth Conference on Building Science and Technology, University of Waterloo, Waterloo, Ontario, 1988, pp. 2–12.
27. Dainty, D.A., et al., "A final report on the evaluation of window opening capacities." Report prepared by University of Ottawa for the National Research Council of Canada, Contract No. 080–082/0–4424, 1981.
28. Covington, S.A., "Ergonomic requirements for windows and doors." Building Research Station, Garston, UK, Building Research Establishment Information Paper IP 2/82, 1982.
29. Shandra, S., K. Ruberg and A. Keresteciogiu, "Outdoor testing of small scale naturally ventilated models." Building and Environment, Vol. 18, No. 1/2, 1983, pp. 45–53.
30. Collin, I.D. and E.J. Collins, "Window selection: A guide for architects and designers." Newnes-Butterworths, London, 1977, pp. 88–89.
31. Dietz, A.G.H., "Plastics for architects and builders." MIT Press, Cambridge, Mass., p. 65.

The System Approach to Window Performance Standards

A.H. Elmahdy and A. Patenaude

Introduction

Windows are a complex element of the building envelope and must be assessed as an independent system, as a part of the building envelope, and as an integral part of the indoor environment. The relationship between windows and the building envelope is covered in the second paper, *Integrating the window with the building envelope*. The interaction between windows and the indoor environment is discussed in the fourth paper, *Window performance factors*. In this paper, the standards and specifications that relate to the window as an independent system are reviewed.

A system can be defined as a product which is designed to perform a multitude of functions, psychological and/or physical. The main reason for installing windows in the building envelope is to maintain viewing areas to the outside world. The psychological benefits from walls with viewing areas versus walls which are completely opaque are numerous. Since the window system is part of the building envelope, it must perform the same basic physical functions as a wall, in addition to other special requirements.

Assessing the performance of a particular window with respect to each of the physical criteria it must meet is an enormous task. The benefits of having a common set of criteria and methods for assessing a product or system such as a window are obvious and do not need elaboration here. The common set of criteria must represent those that are essential to the performance of the system, and any methods of assessing the performance in the laboratory must rank the product in a way that is consistent with its performance in the field. Significant advances in meeting these needs have resulted in the development of a new performance standard, the CSA Standard CAN3–A440–M84,[1] which is the subject of this paper.

Current Canadian Window Standards

Currently, there are several standards available (Table 1). Prior to the development of CAN3–A440–M84, Canadian window standards were mainly written with respect to each different frame material (wood, PVC, aluminum) and operation type. All standards incorporated both prescriptive and performance requirements, which could be very different from one standard to another. Also, for some frame materials (steel fixed, and wood and vinyl storm windows) the window types were not covered, and the standards did not apply to combinations of different frame materials. Consequently, products could not be compared from one standard to another and a need for a common window standard was identified by Canada Mortgage and Housing Corporation (CMHC) and the industry.

The starting point in the development of CAN3–A440–M84 was the notion that *a window is a window*, and will have to perform the same functions whether the frame material is wood, aluminum, PVC or any combination. Ideally, a single performance standard would be developed but this was not practical or economical from the standpoint of the many tests that would be needed to cover all issues related to the product. Therefore, some prescriptive elements were included; these are recognized as common practice, for example, thickness of wood, metal, or PVC.

The A440 Standard was developed by a consensus process, as are other Canadian product standards. A technical committee was formed, which represented a balanced matrix of producers, users, and general interest groups. After several drafts and a lot of hard work by all involved, a standard which represents a consensus of all groups was finally approved.

CAN3–A440–M84 Standard

Test Specimen

A single test specimen is used for the entire series of tests. It is a new factory-assembled window of a specific model, complete with all hardware and screens (if applicable), which is typical of the regular production.

The specimen size is in accordance with Table 2, except when the manufacturer wishes to demonstrate conformance to smaller or larger model size ranges. The outside dimensions of the main frame shown in Table 2 were selected on the basis that about 90% of windows manufactured in Canada would be smaller than the values given.

For windows up to 25% larger (in each dimension) than those shown in Table 2, calculation may be employed to determine compliance with the wind load resistance test. For the other tests, results from a standard size specimen may be extrapolated to larger sizes and compliance with the standard can be claimed. Windows 25% larger (in each dimension) than those in Table 2 must be tested.

Test Sequence

The air leakage test, water resistance test, and wind load resistance test are performed in this sequence. All other tests are performed, as applicable, either before or after these three tests, at the discretion of the testing agency.

Usually, tests are performed in the following sequence:

Common tests

- ease of operation (operable windows only),
- air leakage,
- water penetration resistance,
- wind load resistance.

Table 1 Window standards in Canada

Standard	Type of window	Framing material	Duty
63–GP–1M[2]	h. & v. sliding	aluminum	heavy
63–GP–2M[3]	"	"	medium
63–GP–3M[4]	"	"	standard
63–GP–5M[5]	"	steel	"
63–GP–6M[6]	"	"	medium
63–GP–7M[7]	"	aluminum	heavy
63–GP–8M[8]	projecting (casement, awning, hopper)	"	medium
63–GP–9M[9]	v. sliding (semi-sash)	"	standard
63–GP–11M[10]	storm (h. & v.)	"	"
63–GP–12M[11]	fixed	"	–
63–GP–13M[12]	storm (h. & v.)	"	standard
A274–M1980[13]	v. & h. sliding casement awning hopper	PVC	" medium heavy
O132.1–M1977[14]	v. & h. sliding casement awning hopper sashless	wood	standard
CAN3–A440–M84	all	all	all

Specific tests

- condensation resistance,
- resistance to forced entry,
- safety drop,
- blocked operation,
- sash strength and stiffness (racking or warping),
- screen strength,
- sash pull-off.

The following sections describe the intent of each test, the apparatus and procedure used, and the performance requirements. In some cases comparisons with foreign standards are provided.

Table 2 Specimen sizes for performance tests

Window type	Outside dimensions of main frame (± 100 mm) Width mm	Height mm
v. sliding	1000	1600
h. sliding	1600	1000
casement	700	1600
projecting	1000	1000
fixed	2000	2000

Ease of Operation

Intent

The test measures the force required to initiate and to maintain motion of a movable sash from the fully closed to the fully open position.

Apparatus and test method

Using a spring balance or a torque-meter, the force (or the torque) required to initiate and to maintain motion is measured.

Performance requirements

The measured force must not be greater than the values in Table 3.

Comments

The maximum operating forces selected were based on the ergonomic data available at the time, which suggested that 90% of the population could exert sufficient force to operate the windows. In some special cases, however, operating forces different from those stated in the standard may be specified.

Air Leakage

Intent

The test measures the air flow rate through a window subjected to a positive static pressure differential of 75 Pa. This pressure differential corresponds to the pressure exerted by a 40 km/h wind acting perpendicular to the exterior window surfaces.

Apparatus and test procedure

As shown in Figure 1, the test apparatus consists of:

- a test chamber with an opening to install the specimen,
- an air flow measuring device,
- pressure measuring devices.

The test is conducted in accordance with ASTM E 283–84[15] at a positive (inward) static pressure differential of 75 Pa; the resulting air flow rate is reported in $m^3/h/m$ crack length.

Performance requirements

Windows are rated with respect to the rate of air leakage (m^3/h) per unit of crack length (m) (Table 4).

Comments

Table 4 shows three levels of air leakage rating. This allows the specifier to select windows which meet higher performance requirements than the minimum level (A1). This may be required when windows are installed in some locations in Canada where the wind speed frequently exceeds 40 km/h, or when windows are installed in highrise buildings.

Where windows must function under relatively high wind speed conditions, it may be desirable for the specifier to assess the air leakage characteristics of windows over a range of wind pressures. Therefore in the future the standard may require determination of the air leakage rates of windows over a range of pressure differentials between 0 and 300 Pa.

Table 3 Forces required for ease of operation

Type of window	Point of application of force	Direction of force	Maximum force to initiate motion (N)	Maximum force to maintain motion (N)
Vertically sliding	Midpoint of operating handle(s) or of meeting rail	Vertical, parallel to plane of glass	200	100
Horizontally sliding	Midpoint of operating handle(s) or of meeting rail	Horizontal, parallel to plane of glass	90	45
Casement and projecting with roto-operators	End of crank handle	Perpen-dicular to crank handle and screw	60	30
Casement and projecting with lever type operating hardware	End of lever	Perpen-dicular to lever in the plane of its motion	200	100
Other casement and projecting	Midpoint of sash opposite hinges or operating handles	Perpen-dicular to plane of glass	200	100

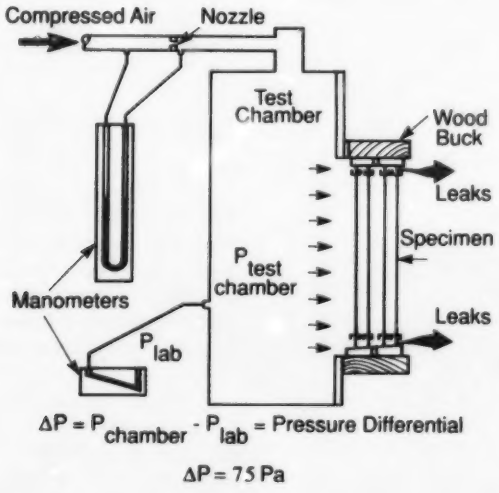


Figure 1. Air infiltration test.

Table 4 Classification, air leakage

Window rating	Maximum air leakage rate per unit of crack length at 75 Pa $m^3/h/m$
A1	2.79
A2	1.65
A3	0.55
Fixed	0.25
Storm	5.0(min) 8.35(max)

Also under consideration, but not approved, is the inclusion of air exfiltration requirements in the standard. This may be an important requirement for windows installed in highrise buildings, where exfiltration usually occurs at levels higher than the plane of neutral pressure in the building. In such cases, windows demonstrate different performance when the pressure is reversed.

Water Penetration Resistance

Intent

The principle is to spray a known quantity of water on the outside surface of the window while applying a cyclic pressure differential across the window that simulates a fluctuating wind pressure on the building. Any water passing into the room side or into the wall, or remaining trapped in the assembly, would constitute a failure of the window.

Apparatus and test procedure

The basic test apparatus consists of:

- a chamber with an opening to install the test window,
- a means of providing a controlled air pressure differential across the window,
- a device for rapid controlled changes of the air pressure differential between defined limits,
- a device to uniformly spray a known water flow over the specimen,
- a device to evacuate water from the test chamber,
- a means of measuring the difference in pressure between the two faces of the window.

Tests are conducted in accordance with ASTM E 547–86[16] (i.e., with a defined static pressure differential across the window and a rate of water flow equal to 3.4 L/min/m^2). At each successive test pressure, four cycles are completed, each cycle consisting of five minutes with pressure applied and one minute with pressure released. Water is sprayed on a continuous basis.

Performance requirements

Windows are rated with respect to the maximum static pressure differential they can sustain without undergoing any water leakage. Table 5 shows the current ratings for water penetration resistance of windows.

Table 5 Classification, water penetration resistance

Window rating	Static pressure differential Pa
B1	137
B2	200
B3	250

A window successfully passes the water resistance test when:

- no water causes wetting of the interior room surfaces,
- no water passes through the window into the wall below the window sill, and
- no water remains trapped in the window assembly upon removal of the air pressure at the end of the test.

Comments

The Canadian window market often receives products from other countries, which have been rated according to their test methods. In order to make a sound judgement when selecting a window, it is beneficial to compare the foreign test method with the Canadian test method.

The test procedure for water penetration adopted by European countries covers a range of static pressure differentials (0 to 500 Pa), which largely exceeds the Canadian standard requirement (up to 250 Pa, see Figure 2). In addition, the test is performed without pressure release between two consecutive levels of performance, and the water flow rate used by European countries (1 L/min/m^2) is much lower than that used in Canada and the United States. Windows rated as commercial and heavy commercial in the United States have to prevent water penetration at higher static

pressure differentials than those required by the Canadian standards.

Future revisions of the Canadian standard may include rating windows according to wind-driven rain pressure in different climatic locations in Canada. For more details, see Appendix A.

Wind Load Resistance

Intent

The objective is to determine the rigidity of sash members and mullions, and to check the strength of a window assembly subjected to extreme static pressure differentials. The amount of deflection is used as an indication of this strength. It is not the intent of this test to assess glass performance unless there are unusual features of the assembly which promote glass breakage.

Apparatus and test procedure

The basic test apparatus consists of:

- a chamber with an opening to install the test window,
- a means of providing a controlled air pressure differential across the window (inward and outward),
- a means of measuring the difference in pressure between the two faces of the window,
- several displacement gauges to measure the deflection of sash members or mullions (see Figure 3).

Performance requirements

Windows are rated with respect to the maximum static pressure differential they can sustain (for 1 minute ± 5 seconds) without deflection exceeding 1/175 of their length (20 mm max.) for mullions and 1/50 of their length (25 mm max.) for sash members. Also, upon completion of the test, there is to be no breakage, failure or permanent deformation of any part of the window. The window classification is established by the pressure levels indicated in Table 6. The test is conducted in accordance with ASTM E 330–84.[17]

Comments

A European standard (Norme française P20–302)[18] states that:

a) under a static pressure differential of 500 Pa, the deflection of sash members does not exceed 1/200 of the span (for residential windows), and
b) when subjected to a specific static pressure differential (class V1, 500 Pa, and class V2, 1000 Pa) sash members retaining an insulating glass unit do not deflect more than 1/150 of their span (for commercial windows).

A Canadian window which satisfies the existing requirement of level C2 will automatically meet item (a). Nevertheless, when insulating glass units are used, the same Canadian window might not meet the requirement of class V2 of the European standard.

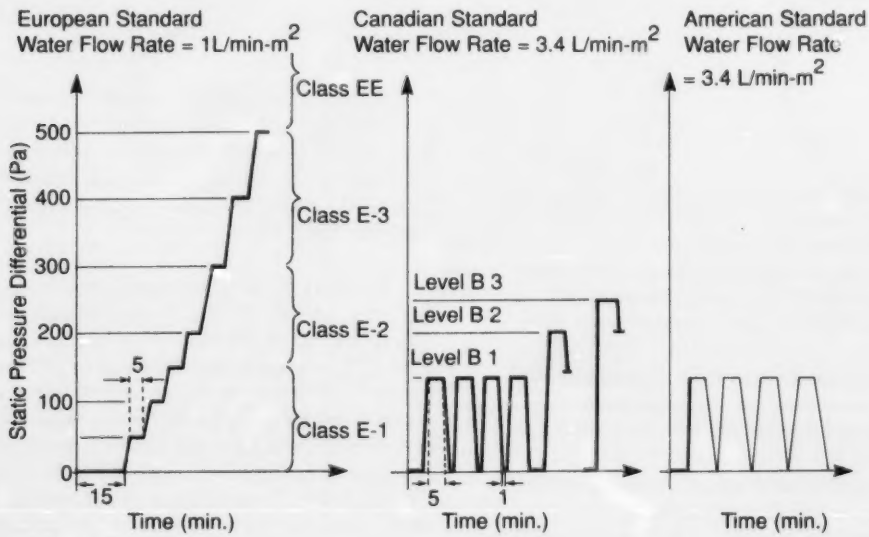


Figure 2. Comparison of standards.

U.S. standards (AAMA 101–85[19] and AAMA 101V–86,[20] using pressure differentials of 1077, 1437 and 2873 Pa) do not have any specific requirements with respect to the allowable deflection at a specific test pressure. U.S. standards only require that there is no permanent deformation of any main frame, sash or ventilator member in excess of 0.4% of its span.

Using the Supplement to the National Building Code of Canada 1985[21] to determine the design pressure for a window (cladding), the required test pressure for blowout may exceed the existing C3 level (Test Pressure = 1.5 × Design Pressure, with 1.5 as a safety factor.)

In order to eliminate such discrepancies, the revised sections of A440 with respect to structural performance may include the evaluation of two specific criteria: wind load resistance to deflection, and wind load resistance to blowout.

A Users Guide, which is intended as an appendix to CAN3–A440–M84, may contain a method by which the user can determine the classification of window required for a given location. The method takes into consideration the following factors: building size, geographic location, height of installation, pressure coefficient and gust factor. Computed test pressures for several elevations above grade corresponding to reference pressures (1/10 year) from 0.2 kPa to 1 kPa, with 0.05 kPa increments, will also be available.

Table 6 Classification, wind load resistance

Window rating	Static pressure differential across the window kPa
C1	± 1.5
C2	± 2.0
C3	± 2.5

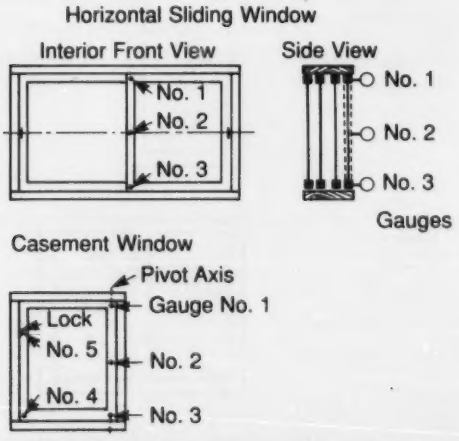


Figure 3. Position of displacement gauges.

The present window standard does not include any requirements with respect to the vertical deflection of horizontal mullions, although the addition of more restrictive failure conditions of horizontal mullions due to deformation and deflection is being considered.

Condensation Resistance

Intent

This test applies only to windows that incorporate metal sash or frame members, or both, in such a way that a thermal break is necessary to avoid through-metal heat conduction. This includes metal sash or frame members, or both, encased in other materials, but does not apply to windows with separate inner and outer sashes mounted in a wood frame.

The effectiveness of the thermal break is measured by the maximum temperature differential between the inner glass and the frame or sash members. The smaller the measured temperature differential is, the better will be the overall performance of the thermal break.

Apparatus and test procedure

As illustrated in Figure 4, the basic apparatus consists of:

- a chamber with an opening to install the test specimen,
- a means of providing cold air on the outside face of the specimen,
- a means of controlling the outside and inside air temperatures,
- a means of measuring the difference in pressure between the two faces of the window,
- thermocouples to measure air and surface temperatures.

Performance requirements

Windows are rated with respect to the maximum calculated temperature difference (ΔT) between the mean inside glass temperature (T_A) and the minimum inside metal surface temperature (T_B), on the basis of 50°C air temperature difference between the warm and cold sides, when an equilibrium condition has been obtained (see Figure 5 for the location of thermocouples).

$(\Delta T)_{cal} = 50 \times T_1/T_2$ (°C)

where:

$(\Delta T)_{cal}$ = maximum calculated temperature difference (°C)
$T_1 = T_A - T_B$ at test conditions (°C)
T_2 = measured air temperature difference between the warm and cold sides (°C)

Table 7 gives the classification of windows with respect to glazing type and $(\Delta T)_{cal}$.

Table 7 Classification, condensation resistance

Window rating	Maximum calculated temperature differential (°C)	
	Sealed unit	Other windows
D1	9	7
D2	4	4

Comments

This test was intended to compare different frames to a 'standard' glazing system. The requirements set for this test are to minimize the temperature differential between glass and frame or sash members. This means that if the thermal performance of the glass portion is improved, the relative performance of the sash or frame drops and a lower rating would result. This is a disincentive to improving glazing without similar improvements to sash or frame. On the other hand, if the glass portion of a window is downgraded with respect to thermal performance and if the sash and frame members are unchanged, the new window could reach the top rating. These anomalies in the test and performance requirements necessitate a review of the current condensation resistance test.

Major modifications to the condensation resistance test procedure as well as the window rating are under consideration. For more details about the proposed changes, see Appendix B.

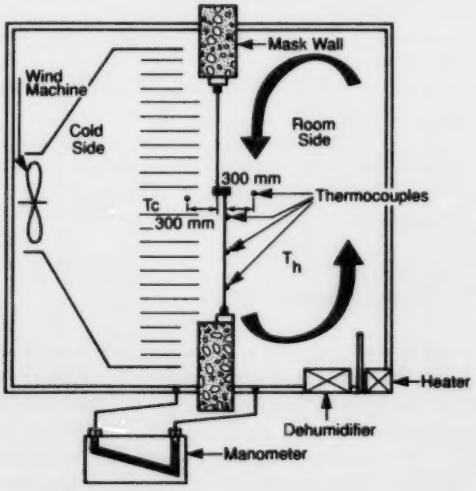


Figure 4. Condensation resistance test apparatus.

Resistance to Forced Entry, ASTM F 588–85 (Optional)

Intent

Undesirable entry to buildings is one of the most common criminal activities in North America; it is escalating annually and is affecting an increasing number of homeowners. The most vulnerable parts of the building envelope subjected to forced entry are: windows within reach of outside intruders, front and back doors, garage doors and patio doors.

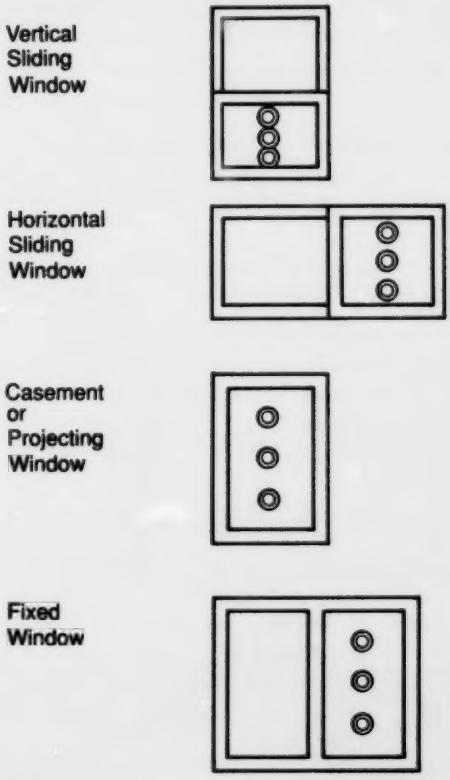


Figure 5. Location of thermocouples to calculate average temperature of glass, interior view.

The test methods described in ASTM F 588–85[22] are intended to establish a measure of resistance for window assemblies subjected to attacks (other than impacting glazing materials) by unskilled and opportunistic burglars. Higher levels of force by skilled burglars may require more sophisticated resistance methods, such as alarms, communication or apprehension systems, or special security glazing materials.

Apparatus and test procedure

The apparatus consists of a steel structure supporting a wood frame wall which has an opening to accommodate the sample. The setup is capable of generating several load forces simultaneously on a working surface of 2.75 m (width) by 3 m (height). The load forces are applied at the appropriate locations with directions and magnitudes as specified by the standard.

The specimen is installed within the supporting wood frame wall as per the manufacturer's normal installation instructions.

The test involves the following:

- a hand manipulation test,
- a tool manipulation test,
- the application of static loads at different locations of the assembly,
- a repeat of the hand and tool manipulation tests.

Performance requirements

ASTM F 588–85 suggests four grades of security (grade 10, 20, 30, 40); grade 10 is the lowest and grade 40 the highest. Only grade 10 performance level is required in the current standard. Table 8 gives the values for time and force required for each level of performance as stated in ASTM F 588–85. To achieve a given rating the sample has to successfully pass the entire test sequence.

Comments

CAN3–A440–M84 mentions only the first level of performance suggested by ASTM F 588–85. Revisions of the existing Canadian standard suggest increasing the number of performance levels and recommend that resistance to forced entry become mandatory. Proposed changes to the National Building Code of Canada suggest that forced entry requirements be changed from "optional" to "mandatory".

Safety Drop (Vertical Sliding Windows with Intermediate Stops)

Intent

The objective is to check that a free falling operable sash will stop at the next lower detent without damaging the window or injuring the window operator.

Apparatus and test procedure

The test consists of raising each operable glazed sash to the highest stop position. Then the stopping handles of a given sash are released to allow the insert to fall freely.

Performance requirements

Following a free drop, the sash should stop in the next lower latch position and should not break, fail or permanently deform any part of the window that would cause a malfunction, or impair the operation of the unit. This procedure is repeated five times for each operable sash.

Table 8 Performance requirements for resistance to forced entry

Time and load identification Symbol	Units	Grade 10	Grade 20	Grade 30	Grade 40
T1	min	5	5	10	10
T2	min	5	5	10	10
L1	N	668	890	1112	1335
L2	N	334	445	556	668
L3	N	111	156	222	289

Blocked Operation (Sliding Window Only)

Intent

This test determines the behavior of an operable sash member (pull rail or meeting rail) when excessive force is applied to the operating device (handle). For example, moisture might freeze around the sash and extra force could be required to open it. Under such conditions, separation of the sash from the glass must be prevented.

Apparatus and test procedure

Figure 6 illustrates the test arrangement for both types of sliding windows. The test is conducted on the pull rail and the meeting rail, if the latter can be used as a handle. The relative displacement of the operating sash member versus the glass is measured at mid-span (see Figure 7).

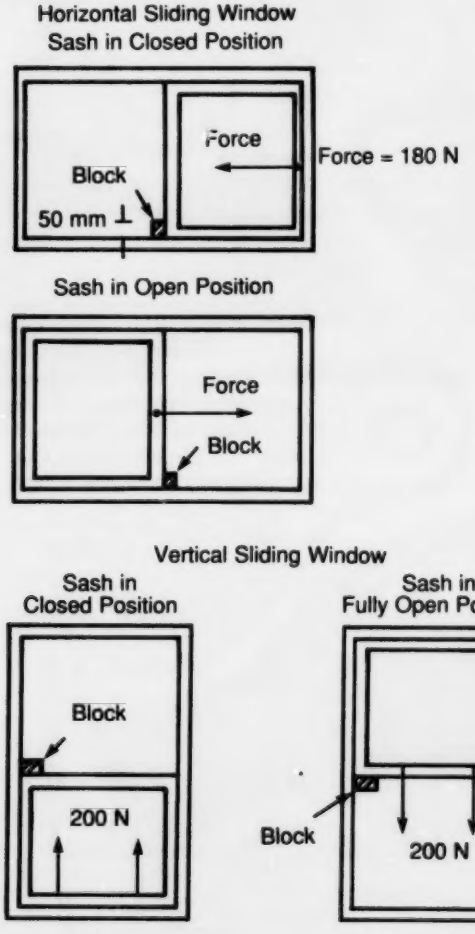


Figure 6. Blocked operation test.

Performance requirements

Under the specified force (400 N for vertical slider, and 180 N for horizontal slider) each sash must comply with the following requirements:

- when measured at mid-span of the operating sash member, the initial relative displacement of sash member versus glass should not exceed 75% of the engagement design value. The residual relative displacement, five minutes after the test force is removed, should not exceed 50% of the engagement design value,
- upon completion of the test, the operating handles should remain firmly attached to the sash member and should show no signs of failure or permanent deformation, and
- the glazing should not break.

Sash Strength and Stiffness (Racking – Casement Windows Only)

Intent

This test determines the behavior of a casement window when an additional vertical force is applied at the outer free edge of the open sash. Although this is considered a misuse of the window, the sash should have some resistance in case someone grabs the open casement and pulls down on the sash.

Apparatus and test procedure

The test consists of applying a downward vertical force of 265 N, at a distance of 50 mm in-board of the

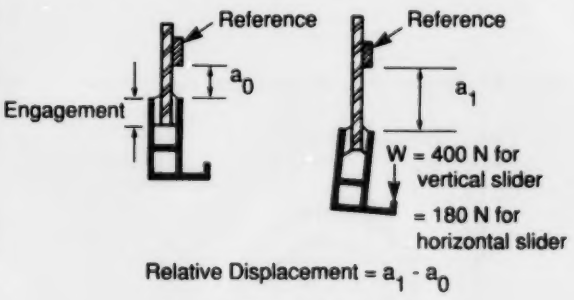


Figure 7. Blocked operation test.

outer free edge of the operable sash opened at 90° or to the limit of its travel, whichever is less. Figure 8 shows a typical window under test conditions.

Performance requirements

The window must comply with the following requirements:

- the vertical deflection of the lower outer corner of the sash must not exceed 5 mm when the load is applied,
- upon completion of the test, neither the main frame nor the sash should show any signs of failure of materials or permanent deformation that would impair the operation of the window.

Sash Strength and Stiffness (Warping – Projecting Windows Only)

Intent

This test determines the behavior of a projecting window when the sash is open and a force is applied perpendicular to its plane in the closing direction, while a corner of the sash is jammed. This situation could happen when the latch that holds the operable sash in the 'open' position is jammed while someone tries to close the sash.

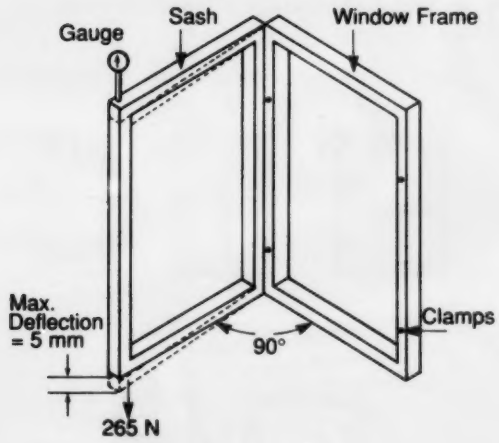


Figure 8. Racking test, casement window.

Apparatus and test procedure

Figure 9 shows a test sample in place. The test consists of opening the sash at 45° or to the limit of its travel (whichever is less), and blocking one free side of the sash member opposite the axis of rotation in order to prevent closing. A force of 60 N is then applied at mid-span of the sash member opposite the pivots in the closing direction and perpendicular to the plane of the glass. The deflection of the free corner is measured.

Performance requirements

The window must comply with the following requirements:

- the deflection of the free corner must not exceed 18 mm when the load is applied,
- upon completion of the test, neither the main frame nor the sash should show any signs of failure of materials or permanent deformation that would impair the operation of the window.

Screen Strength (Windows with Operable Sashes Only)

Intent

This test evaluates the attachments holding a screen to a window frame when a force is applied perpendicular to its plane in the outward direction. This condition might occur when someone accidently pushes the screen outward or throws an object at it. Screens are not intended as barriers or a means of safety against heavy objects.

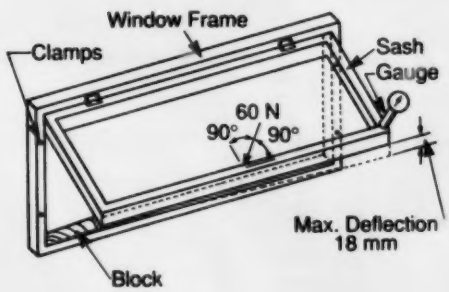


Figure 9. Warping test, projecting window.

Apparatus and test procedure

The test consists of placing the window with a screen in a horizontal position; then applying a force of 60 N (for a standard duty screen) or 330 N (for a heavy duty screen) to the center of the screen (the load is distributed evenly over a circular area 300 mm in diameter) in the outward direction of the window unit. All obstructions that might interfere with the sag that may occur are removed. The load is allowed to remain for one minute.

Performance requirements

A screen satisfies a given rating if upon completion of the test it fulfills the following requirements:

- the screen unit remains firmly anchored to the window, and the mounting fittings do not show signs of failure or permanent deformation,
- the screening material does not tear and remains firmly anchored to the screen sash,
- the screen sash members and their corner connections do not show evidence of failure or permanent deformation.

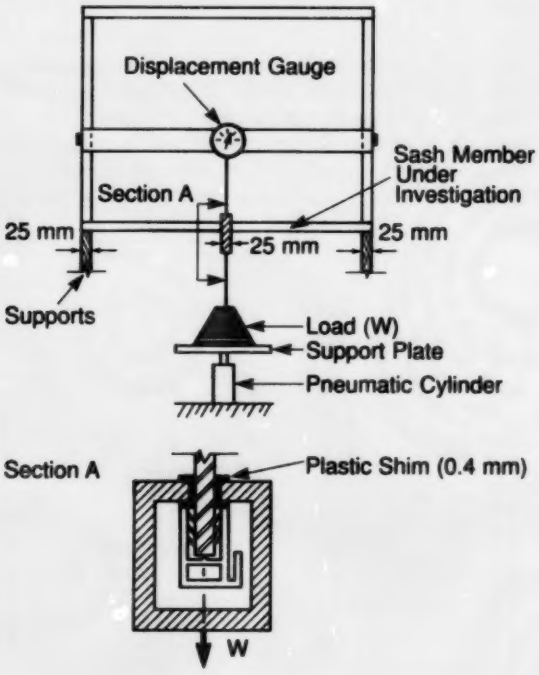


Figure 10. Sash pull-off test, vinyl window.

Sash Pull-Off (Vinyl Windows Only)

Intent

This test determines the rigidity, or glass adherence, of PVC sash members when a force parallel to the plane of the glass is applied at the center of each sash member. The applied force is selected to simulate the creep effect of vinyl that results from exposure to environmental conditions.

Apparatus and test procedure

Figure 10 illustrates the components of the test apparatus. The test consists of applying a given load (see Table 9 and Figure 11) at the center of each sash member and then measuring the resulting deflection.

Performance requirements

When subjected to the load specified in Table 9, no member shall sustain a deflection exceeding 75% of the engagement between members and glass. The load is applied for a period of one minute.

Composite and Combination Windows

A composite window consists of an arrangement of two or more types of windows mounted in one main frame. Figure 12 illustrates a typical composite window.

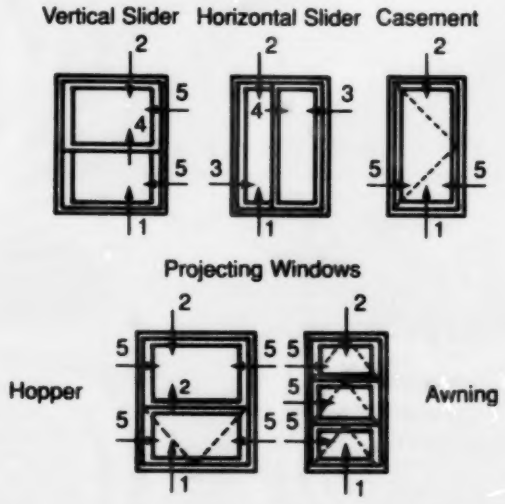


Figure 11. Sash pull-off test, location of load.

A combination window consists of an arrangement of two or more types of windows which are fixed together at their main frames. Figure 13 illustrates a typical combination window.

The existing A440 standard refers to composite and combination windows as follows:

Where the manufacturer wishes to demonstrate compliance with this Standard for composite windows, each of which has been shown to comply individually, it is only necessary to demonstrate that the mullions separating the individual windows have sufficient strength and stiffness to support these windows when subjected to the appropriate wind pressure for the window-class in question. This can be demonstrated either by subjecting the composite window to the wind load resistance test or by testing the mullion as a beam.

This statement raises many questions which the revised 1989 edition of the standard may address. Some of these questions are:

- How can we ensure that the connecting members are continuous, lengthwise and at the joints (against air and water penetration)?
- What happens to the operation of the awning window if the weight of the top window creates a deflection that exceeds the gap between the horizontal mullion and the awning sash?
- What should be the maximum allowable vertical deflection of the intermediate mullion?
- If the mullion is tested as a beam, where should the loads be applied? What will be the magnitude of the loads? What will be the method of calculation used?

Field Installation of Windows

The subject of field installation of windows is included in the standard as a 'non-mandatory' appendix. It covers only the basics of window installation. More details about field installation of windows are given in the fourth paper, *Integrating the window with the building envelope.*

Future Modifications or Additions to CAN3–A440–M84

Future modifications or additions to the existing standard can be divided into short-term and long-term revisions.

Table 9 Loading for sash pull-off test

Type of unit	Sash member	Part No. (refer to Figure 12)	Loading in kg		
			Laid-in glazing	Channel glazing	Semi-sash
V. Sliding	Lift rail	1		45	45
	Top rail	2		27	27
	Check rail	3	27		
	Meeting rail or meeting stile	4		45	45
	Stile	5		27	27
H. Sliding	Bottom rail	1		27	27
	Top rail	2		27	27
	Pull rail, pull stile, or side rail	3	27	45	45
	Check rail, meeting rail, or meeting stile	4		45	45
Casement	Bottom rail	1			
	Top rail	2	27	45	NA
	Stile	5			
Projecting	Bottom rail	1			
	Top rail	2	27	45	NA
	Stile	5			

For the short-term revisions, the following changes may be made:

- the existing condensation resistance test may be improved and PVC and wood windows may be included to satisfy the same requirements,
- procedures for testing composite and combination windows may be included,
- durability may be made mandatory for components such as: rollers, weatherstripping, sash balances, hardware (levers and roto-operators, locks, restricted and located opening devices, etc.),
- air exfiltration tests may become mandatory,
- new ratings for the ease of operation may be introduced,
- higher levels of rating for water resistance and wind load resistance may be added,
- the revised edition of CAN3–A440–M84 will probably include a Users Guide to supplement the standard. This guide will provide data and methods to determine the classification of a window system. It will cover the following criteria: air leakage, ease of operation, and resistance to water penetration, wind loads and condensation.

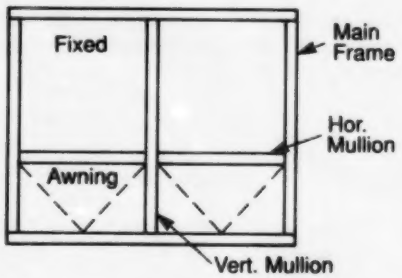


Figure 12. Composite window.

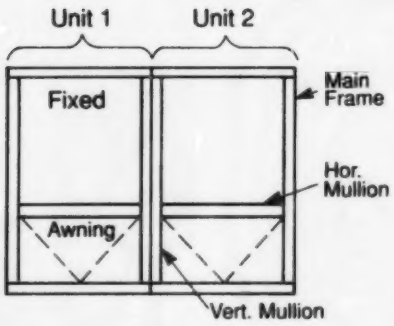


Figure 13. Combination window.

The long-term improvements or additions may include the following:

- measurement of the overall thermal resistance (RSI value) of a window,
- measurement of sound transmission through a window,
- measurement of air leakage at several temperature differentials,
- a weather cycling test prior to testing for all the performance requirements.

Summary

This paper presented the assessment of a window as a system. The review of the CAN3–A440–M84 standard showed that the window is subjected to a comprehensive series of laboratory tests to ensure compliance with the minimum requirements as outlined in the standard.

Many other issues will be examined, analyzed, and presented to the Canadian Standards Association for possible inclusion in future issues of the standard. A well developed standard, based on the best technical knowledge available, will assist the Canadian window industry to compete in national and international markets.

References

1. "Windows." Canadian Standards Association, CAN3–A440–M84, 19 p.
2. "Windows, extruded aluminum, vertical and horizontal sliding, heavy duty." Canadian General Standards Board, 63–GP–1M, 1977.
3. "Windows, extruded aluminum, vertical and horizontal sliding, medium duty." Canadian General Standards Board, 63–GP–2M, 1976.
4. "Windows, extruded aluminum, vertical and horizontal sliding, standard duty." Canadian General Standards Board, 63–GP–3M, 1976.
5. "Windows, steel, vertical and horizontal sliding, standard duty." Canadian General Standards Board, 63–GP–5M, 1976.
6. "Windows, steel, vertical and horizontal sliding, medium duty." Canadian General Standards Board, 63–GP–6M, 1976.
7. "Windows, extruded aluminum, casement, heavy duty." Canadian General Standards Board, 63–GP–7M, 1977.
8. "Windows, projecting metal, medium duty." Canadian General Standards Board, 63–GP–8M, 1977.
9. "Windows, extruded aluminum, semi-sashed, vertical sliding, medium duty." Canadian General Standards Board, 63–GP–9M, 1978.
10. "Windows, metal, combination, storm and screen." Canadian General Standards Board, 63–GP–11M, 1977.
11. "Windows, metal, fixed." Canadian General Standards Board, 63–GP–12M, 1977.
12. "Windows, aluminum, combination, storm and screen, standard duty." Canadian General Standards Board, 63–GP–13M, 1978.
13. "Vinyl windows." Canadian Standards Association, A274–M1980.
14. "Wood windows." Canadian Standards Association, O132.1–M1977.
15. "Test method for rate of air leakage through exterior windows, curtain walls, and doors." American Society for Testing and Materials, E 283–84, 1984.
16. "Test method for water penetration of exterior windows, curtain walls, and doors by cyclic static air pressure differential." American Society for Testing and Materials, E 547–86, 1986.
17. "Test method for structural performance of exterior windows, curtain walls, and doors by uniform static pressure difference." American Society for Testing and Materials, E 330–84, 1984.
18. "Caractéristiques des fenêtres." Association française de normalisation, Norme française homologuée P20–302, 1980.
19. "Voluntary specification for aluminum prime windows and sliding glass doors." American Architectural Manufacturers Association, AAMA 101–8501, 1985.
20. "Voluntary specification for poly(vinyl chloride) (called PVC) prime windows and sliding glass doors." American Architectural Manufacturers Association, AAMA 101V–86, 1986.

Appendix A

Proposed Changes in the Resistance to Water Penetration Test

The CSA committee in cooperation with Environment Canada are conducting a study on wind-driven rain pressures (WDRP) for the Canadian climate. A climatological analysis based on the frequency distribution of wind pressures during rain at a height of 10 m above ground was developed. This pressure distribution (with an acceptable maximum probability of occurrence) will be used as the water leakage test pressure differential. To cover building heights over 10 m, a height coefficient is also included in the analysis.

A rainfall rate of 1.8 mm/h (light rain) was selected. Because of the amplification created by wind on a vertical surface, this amount of water is sufficient to wet the exterior surface of the window. A one-minute average hourly wind pressure was selected as representative of wind pressure. No allowances have been made for exposure of the building, terrain and pressure coefficients, in order to produce an easy-to-use procedure.

Table A-1 gives the wind-driven rain pressures for various locations in Canada. The required test pressure differential for different reference pressures versus the installation height of a window will be tabulated in the standard.

The proposed Users Guide for CAN3–A440–M84 will contain the reference wind-driven rain pressure for 640 locations across Canada. In addition, a contour map of pressures will be produced showing contours at intervals of 10 Pa, to assist the user with locations other than the main 640 listings.

As suggested by the reference wind-driven rain pressures given in Table A-1, the existing ratings would need to be revised with respect to resistance to water penetration. Table A-2 gives the proposed new ratings for water resistance.

Table A-1 Wind-driven rain pressures

Location	Reference pressure (Pa)
Port-aux-Basques	495
St. John's, Nfld.	477
Charlottetown	362
Halifax	316
St. John, N.B.	296
Winnipeg	237
Montreal	225
Saskatoon	207
Toronto	179
Edmonton	155
Vancouver	149
Kamloops	117
Yellowknife	114
Whitehorse	56

Table A-2 Proposed new rating

Rating	Water leakage test pressure, Pa
B1	150
B2	200
B3	300
B4	400
B5	500
B6	600
B7	700

Appendix B

Proposed Changes to the Condensation Resistance Test

The proposed condensation resistance test is intended to compare the resistance of windows to condensation on interior (warm side) surfaces when exposed to a single set of standard test conditions.

Test results will provide a temperature index (I) applicable to the glass and framing parts of a window. The temperature index will allow the prediction of the condensation resistance of a window for other sets of operating conditions (indoor relative humidity (RH), and outdoor dry-bulb temperature).

The proposed condensation resistance test procedure describes how the test window is to be mounted in an environmental chamber capable of simulating indoor and outdoor conditions. The procedure also specifies the temperature measurements required to determine the temperature index for the glazing and frame separately.

During the test and when the steady-state is reached, the average (of five consecutive observations) room-side (T_h), weather-side (T_c), minimum frame (T_f), and minimum glass (T_g) temperatures are recorded. T_g is the average of three temperature readings on the coldest glass surface (Figure B-1).

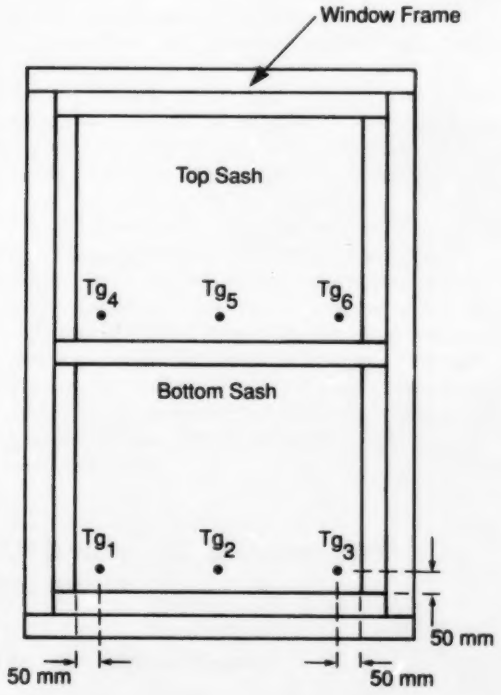


Figure B-1. Location of thermocouples.

The temperature index (I) is defined as follows:

$$I = (T - T_c)/(T_h - T_c) \times 100\%$$

where T is the lower of T_g and T_f. Therefore:

$$I_g = (T_g - T_c)/(T_h - T_c) \times 100\%, \text{ and}$$

$$I_f = (T_f - T_c)/(T_h - T_c) \times 100\%$$

The following procedure illustrates how to select a temperature index (I) for a given window, in a given location in Canada:

1. Select the inside design relative humidity to be maintained without causing condensation:
   - design criteria can be different for the frame members and the glass area or it can be the same,
   - the indoor design dry-bulb temperature (T_h) is taken as 20°C.
2. Select the outside winter design temperature (T_c) for the location where the window will be installed, for example –15°C. This value can be found in the Supplement to the National Building Code.
3. Using Figure B-2:
   a) enter the values of relative humidity (RH) found in step 1 on the vertical scale, for example:
   Max. RH_{glass} = 30%
   Max. RH_{frame} = 30%

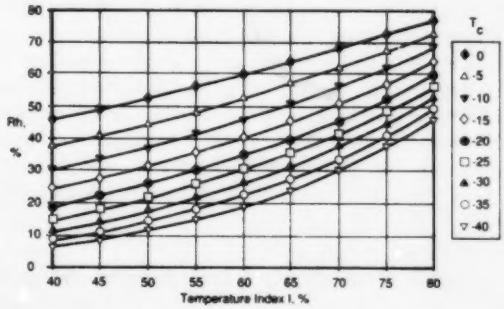


Figure B-2. Relationship of temperature index and relative humidity for different winter design temperatures.

b) move horizontally to the selected outside winter design temperature ($T_c = -15°C$). Linear interpolation may be done;

c) from intersection of each maximum allowable RH and T_c, move vertically downward to find the minimum required temperature index (I) for each case.

Min. (I_{glass}) = 48%
Min. (I_{frame}) = 48%

Table B-1 shows the temperature index (I) for some selected locations in Canada.

Table B-1 Temperature index (I)

	Vancouver	Saskatoon	Winnipeg	Toronto	Montreal	Halifax	St. John's
Inside design conditions							
T_h(°C)	20	20	20	20	20	20	20
RH(%)	35	35	35	35	35	35	35
Outside design temperature (2 1/2%)							
T_c(°C)	–7	–35	–33	–18	–23	–16	–14
I(%)	41	71	70	58	63	57	53

Integrating the Window with the Building Envelope

A. Patenaude, D. Scott and M. Lux

Introduction

Detailing the installation of windows in the building envelope requires a clear understanding of how the window and wall elements are joined and operate as a system. Continuity must be maintained between elements in the window and wall that provide weather protection, airtightness and resistance to heat flow and vapour diffusion. The window design must minimize the potential for condensation on the window or frame that could be caused by improper frame detailing or installation in the wall. Vertical structural loads on the window must be minimized and windows given adequate support and anchorage in the rough opening to ensure that wind loads are properly transferred to structural elements of the wall. Joints and anchorage between the building envelope and window need to be designed to accommodate thermal movement of the window in relation to the remainder of the building.

A good window installation requires team work. The manufacturer must understand what level of performance is required and know details of the final enclosure configuration. The architect must provide details that describe the joints or connections between window and wall. This must be done in a way that allows proper construction by the contractor and on-site trades. Quality assurance for the final performance is distributed between the manufacturer, architect and general contractor.

Continuity of Window–Wall Elements

The Air Barrier System

The air barrier system must be continuous across the entire building envelope to provide effective air leakage control. To assure continuity across windows the designer must be able to identify the elements in the wall and window that provide the air barrier function. The drawings must clearly show how the wall and window systems are connected. Some window frame designs greatly facilitate the joint between the air barrier and the window by providing a pre-designed location where it can be clamped against the frame. This allows for the air barrier system to maintain structural strength against substantial wind forces, and to resist creep or failure by slow deterioration or separation of the sealed joint.

The masonry wall illustrated in Figure 1 employs a reinforced modified asphalt membrane that is self-adhered and mechanically fastened to the concrete block backup. The mason leaves extra membrane material that is later joined to the frame section with a mechanically fastened 'D' section. This section becomes a finishing channel for the drywall window reveal. The air seal in the window is provided by the frame section inside the thermal break and the glazing unit seal at the frame. For residential installations, polyethylene is often used for airtightness. Wood windows, which are often installed in residential applications, can be sealed to the wall by caulking and/or clamping the polyethylene to the window frame. A common method now is to install a separate polyethylene "boot" around the window that then can be connected to the main polyethylene barrier and clamped behind the drywall.

Weather Protection: Controlling Rain Leakage

The weather tightness of a window installation depends on proper selection of window characteristics, and adequate detailing to deflect rain entry at the connection with facade elements. The proper function of the air barrier system is a prerequisite to obtaining

weather tightness. The commercial window in Figure 1 employs the rain screen principle, in which the line of airtightness provided by the inner glazing seal at the frame is protected by a pressure equalized and drained cavity at the bottom of the sealed unit. Rain is deflected away from the window with a neoprene or EPDM glazing gasket that operates effectively if the weep holes in the cavity behind are large in relation to imperfections in the inner air seal. This assures that pressure is equalized across the gasket.

Flashing at the head of the window must lead water to the building face. Care should be taken to select materials that can withstand the rigours of a mason's trowel. The sequence of construction must allow for installation of the flashing at the proper time and location. Caulking at the intersection of the window frame and surrounding material is a rain deterrent and will be treated in a later section.

Sill extensions bridging an external cavity in climates subject to rapid freeze-thaw cycles should be designed to have enough slope to clear the sill of snow before ice develops or be flat enough to allow ice retention and controlled melting.

Vapour Diffusion Control

If adequate vapour diffusion control is provided across the opaque portion of the building envelope, vapour diffusion across a small gap at a window–wall junction is seldom significant.

Thermal Insulation

Continuity of the thermal barrier is important primarily to reduce condensation potential on the interior glazing and interior finish surfaces, and also for energy considerations, interior comfort and thermal environment. Thus, there must be consideration of the location of thermal insulating materials with respect to the location of glazing and interior finishes. The installation of the window in cold locations should be

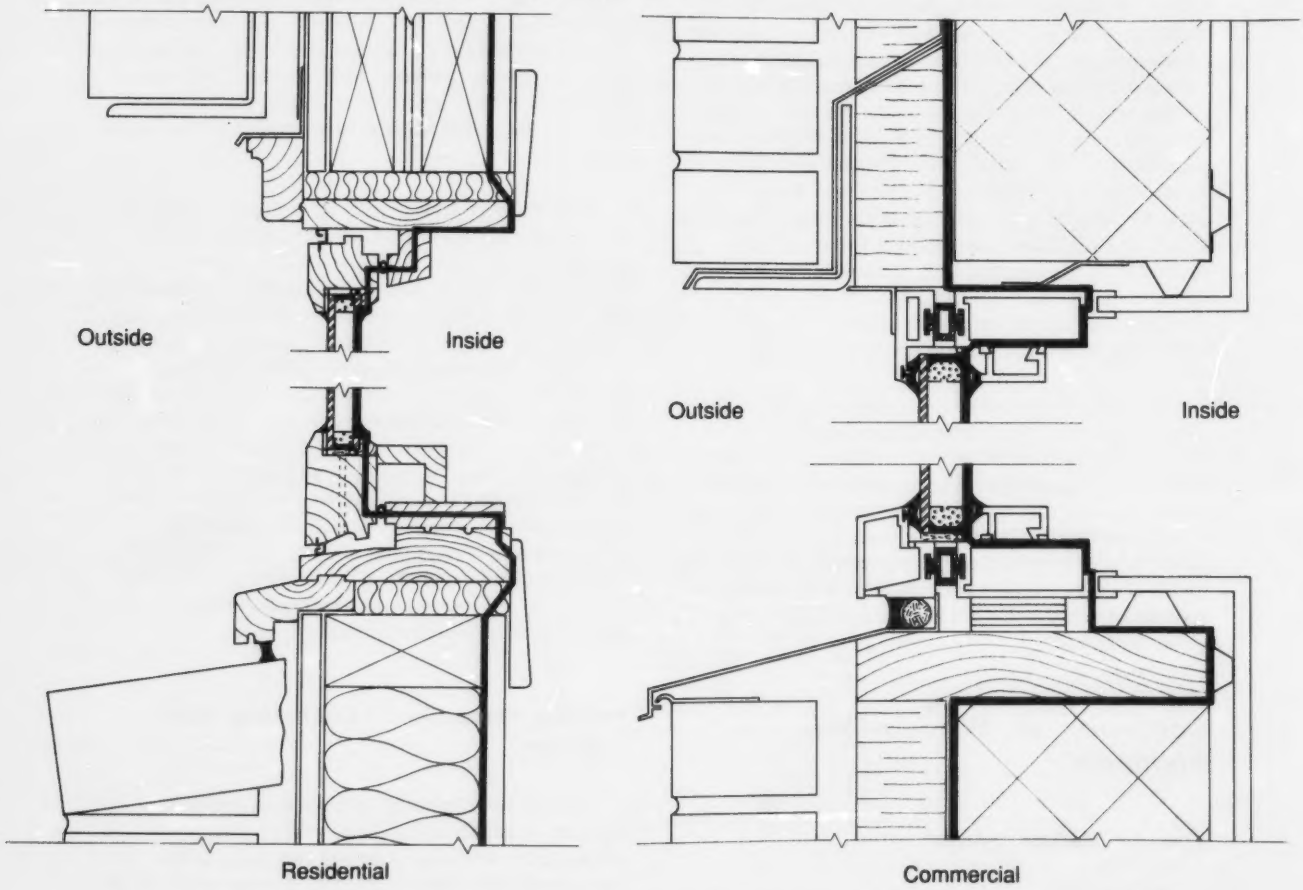


Figure 1. Continuity of air barrier, vapour barrier, weather protection and thermal resistance between window and wall.

avoided. This will be discussed in further detail in the next section.

Thermal Performance: Reducing Condensation Potential

Window Characteristics

In laboratory tests, windows have an insulating mask surrounding the unit that reduces the influence of external factors on the thermal performance of the product. In practice, however, many factors combine to affect the temperature of the glazing and frame components of a window, and thus its condensation potential. Window frame profiles should be carefully scrutinized to identify potential thermal problems related to condensation. To reduce these problems, designers should attempt to maximize the inside surface temperature.

The location of the thermal break is critical in relation to the location of the window in the wall. Care should be taken to eliminate the infiltration of cold air past the thermal break (Figure 2). The amount of window frame exposed to the interior and exterior is important. The area of the frame exposed to the exterior should be smaller than the interior exposed area. This will allow surface temperatures on the edges of the glass and the interior frame section to be higher, and reduce condensation potential. Similarly, the exterior glazing

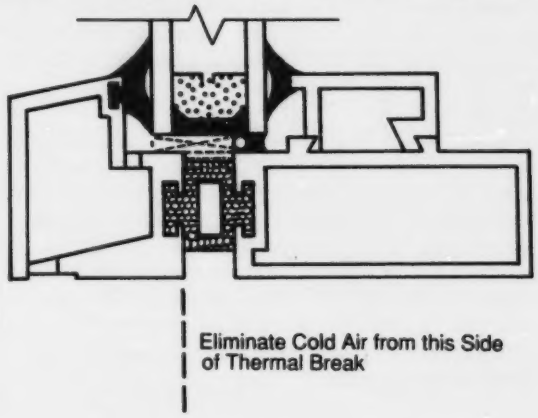
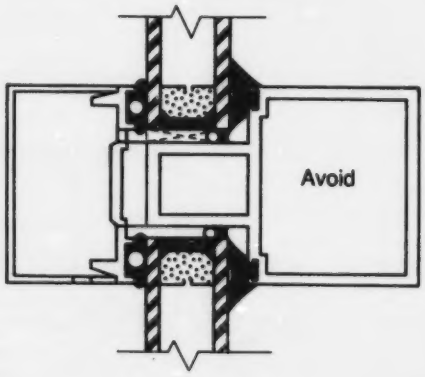


Figure 2. Thermal break in the frame.



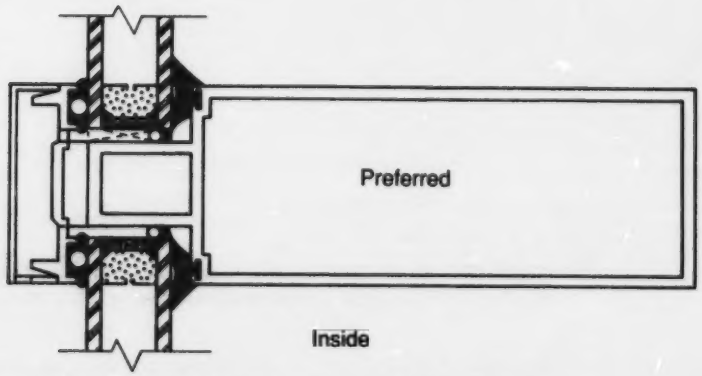


Figure 3. Increasing frame area exposed to heated space.

shim tape should be thicker than the interior glazing seal. Again, surface temperatures at the edge of the glass will be higher and condensation potential will be reduced (Figure 3).

Care must be exercised when combining windows in configurations that result in increasing the fin area exposed on the cold side, such as for a bay or bow window. A thermal break that appears adequate in a test involving a regular window may not be adequate for the heat loss potential in the revised configuration (Figure 4).

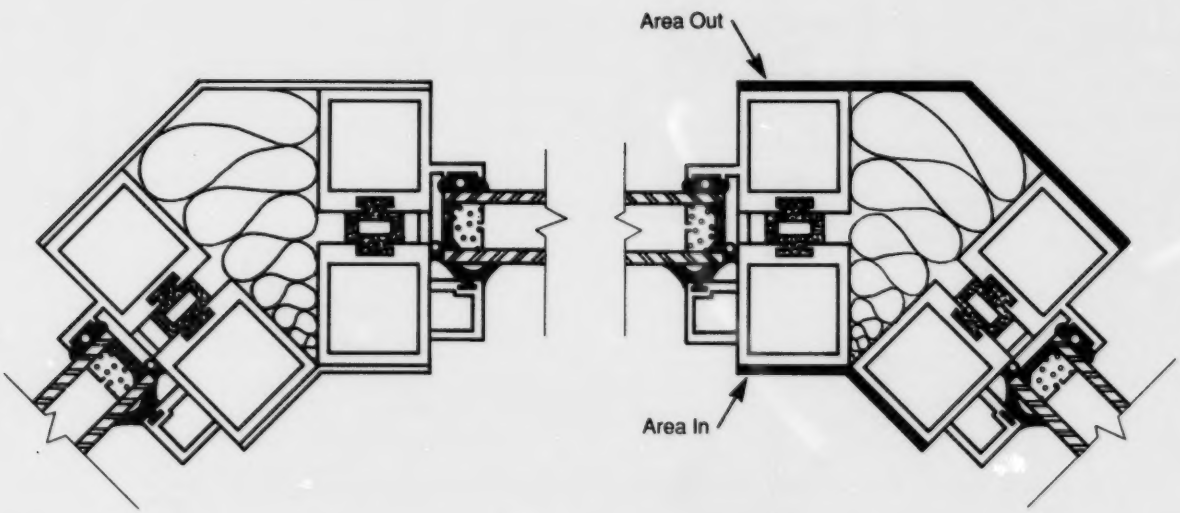
Room side metal frame extensions on the sill or jambs increase heat flow to the frame section inside the thermal break, resulting in higher resistance to condensation. This can be further enhanced by a direct connection to a convector unit under the window (Figure 5). By the same token, interior finishes that effectively insulate the inside frame section from room heat will decrease the frame temperature and increase condensation potential.

Window Reveals

Figures 6 and 7 illustrate problems and attributes of exterior and interior window reveals in relation to condensation potential. Windows installed at the exterior of the wall, away from the interior finish, or shielded from the interior space by close fitting curtains may not get adequate heat delivery. Surface temperatures may be reduced so that condensation potential is increased.

Tolerance Considerations for Window–Wall Junctions

Designers must accommodate a variety of loading conditions on windows with full awareness of dimensional inaccuracies introduced by site construction techniques. The rough opening dimensions may vary from working drawings and are often out of square. Vertical loads that could be introduced by building creep in the first few years after construction must be accommodated. Anchorage systems must transfer wind loads to the wall structure, yet allow differential expansion between the window and wall.



- When units tested: $Area_{out} = Area_{in}$

After combination:

- $Area_{out} \geq Area_{in}$
- Mullions have lower resistance to condensation
- RSI value of mullion will be less

Figure 4. Influence of increasing the outside exposed area, bay window.

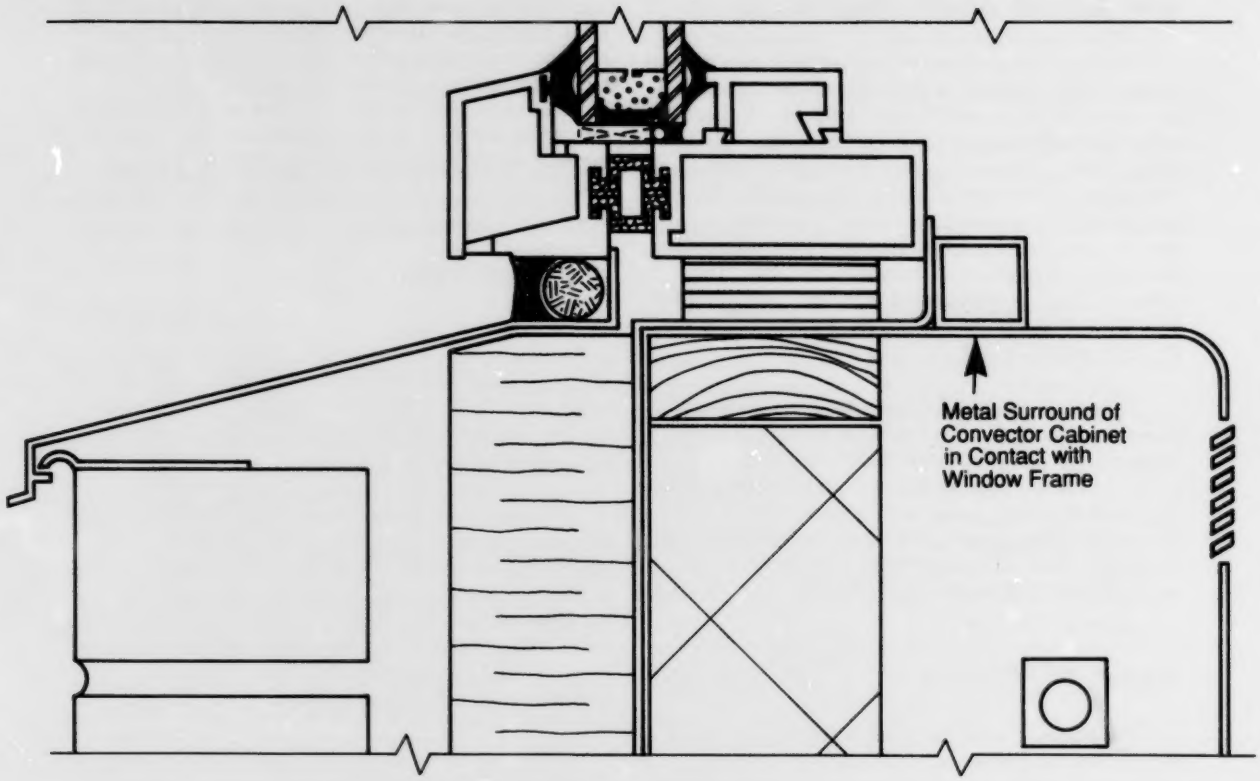


Figure 5. Increasing inside fin area.

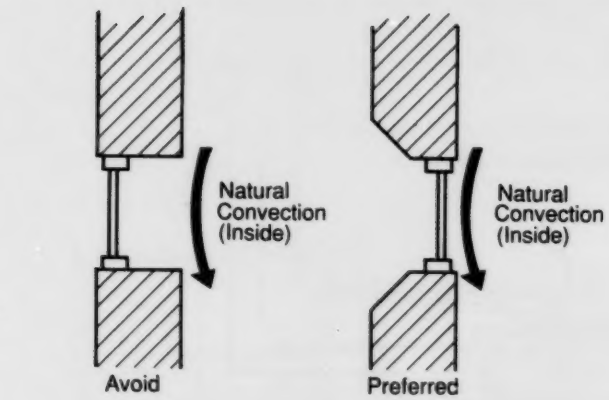


Figure 6. Influence of increasing the inside heat transfer film resistance.

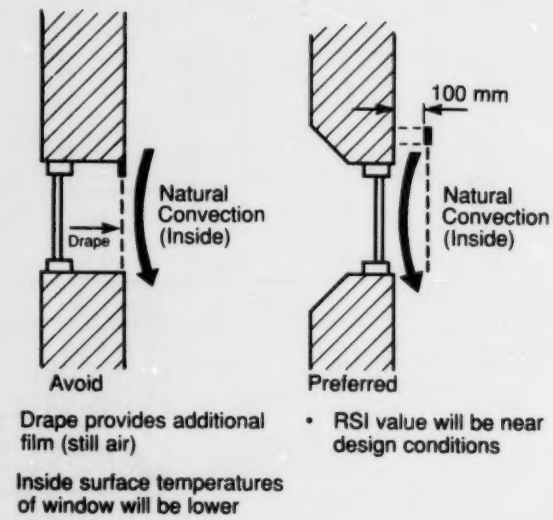


Figure 7. Restricting heat delivery to the window.

Load Transfer Around Windows

Windows are designed to support their own internal weight. When downward vertical loads are transferred to the head of the window frame, deflection will occur and loads might then be transferred to sashes and/or glass. These load transfers will affect ease of operation, or possibly induce stresses on the glazing unit. Therefore, vertical loads above the head of a window frame must be transferred to a lintel or other structural system that limits deflection to an acceptable amount. The deflection must be accommodated when calculating the joint width between the head of the window frame and the lintel above.

To limit vertical load transfer between lintel and frame head, the seal at the top of the window must be compressible using very little force. This is done by using an elastic sealant with a low modulus of elasticity. The window anchor points should allow vertical movement of the window frame head, while minimizing the vertical load component being transferred to the frame. Figure 8 illustrates this principle.

Support for Windows

The bottom part of the window frame or sill must remain horizontal when vertical loads are applied. These loads include the window itself and loads applied during normal use (for example, a person leaning over the sill or a person stepping on the sill of a patio door). The number and location of supports are chosen to minimize deflection on the window frame or sill with the anticipated loads applied.

Material for shimming frames and setting blocks for glazing units must have sufficient hardness to sustain the load for an indefinite period without creeping, allow for anchoring and be a good thermal insulator. Figure 9 illustrates how loads within a window are transferred to the supporting wall. Structural elements in the supporting wall should provide continuity of the load bearing path.

Anchorage Systems

Window anchorage systems must transfer substantial wind loads (positive and negative) to the adjacent wall, accommodate structural deformations such as creep, and allow for thermal expansion between materials. As window units get larger the design of anchorage systems become more critical.

To restrict the displacement of the window versus the wall, several anchor points will be required. Figure 10 represents a large window on which point "A" is a reference point, at mid span on the sill. Point "A" prevents motion in all directions, point 'B' allows only vertical displacement, and the remaining points transfer the wind load (Z) in a manner that accommodates thermal expansion and contraction.

Thermal Expansion

Materials expand and contract at different rates with rising and falling temperature. The term to measure this, known as the coefficient of linear thermal expansion, is expressed as the change in length per unit length for

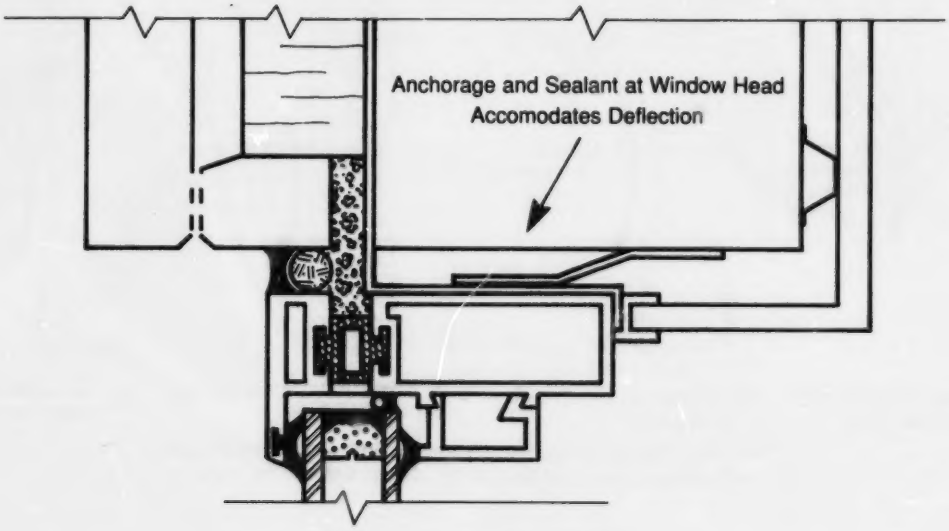


Figure 8. Anchorage at window head.

each degree of temperature change. Materials with high coefficients, such as aluminum or PVC, must have anchorage systems that allow for movement of the joint, when installed in walls made of wood or brick (see Table 1).

The amount of expansion or contraction for a given material is given by the product of the coefficient, the length and the temperature change of the material. The formula may therefore be written:

$$\Delta L = \alpha \times L \times \Delta T$$

where: ΔL = amount of expansion (mm),
α = coefficient of linear expansion for the given material (mm/mm/°C × 10^{-6}),
L = distance between two points of anchorage on the frame (for example, between fixed point "A" and the next anchorage point),
ΔT = temperature variation expected (°C).

To determine joint movement at any anchorage point the following must be known:

- the difference in the coefficient of expansion between the frame (F) and rough opening (O) material ($\alpha_F - \alpha_O$),
- the distance between anchor point "A" and the anchorage point under consideration,
- the temperature difference the window and wall are likely to undergo during the window's service life. The temperature difference of the window may be higher or lower than that of the wall, as discussed later.

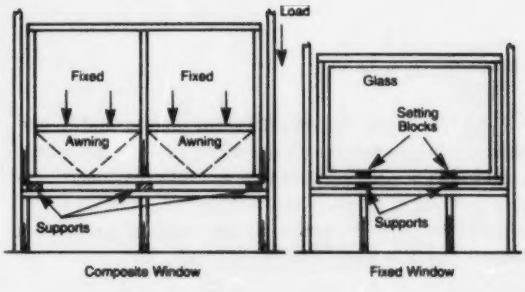


Figure 9. Support for windows.

The change in thermal expansion of the frame versus the opening (F-O) can be calculated as follows:

$$\Delta L_{F\text{-}O} = [(\alpha_F \cdot \Delta T_F) - (\alpha_O \cdot \Delta T_O)]\, L$$

Surface temperatures will vary depending on the ambient temperatures, solar radiation and the thermal mass of the building exterior.[1] Thus the temperature variation of a brick wall would be less than the temperature variation of a light aluminum window frame.

As an example, Figure 11 shows a window installed in a brick wall. The window may be subjected to a temperature range of 100°C. The brick surface temperature variation may be 80°C. Joint movements with respect to point "A" are listed in Table 2 for different frame materials.

Table 1 Coefficient of linear expansion

Material	Coefficient of linear expansion (mm/mm/°C × 10^{-6})
Wood (with grain)	3.8 to 6.5
Brick	5.6 to 6.3
Glass	9.2
Concrete (gravel aggregate)	11.7
Structural Steel	12.0
Aluminum	23.2
PVC	80

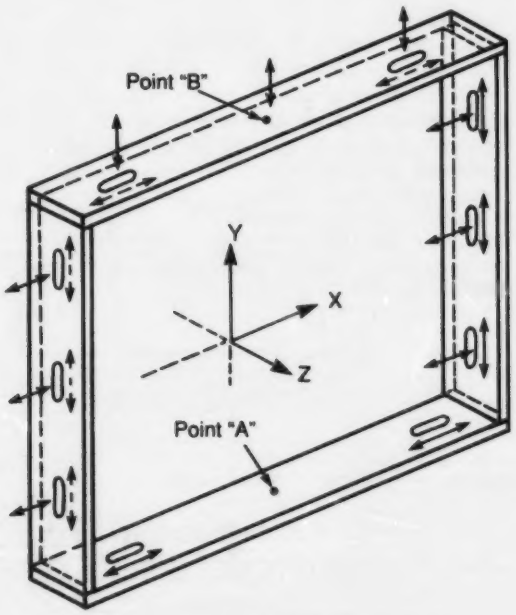


Figure 10. Anchorage points and their respective degrees of freedom.

Installation crews must assess the ambient temperature conditions at the time of the installation to determine whether the window frame material is likely to elongate further with temperature rise or contraction. This naturally will affect the location of the fastener in the slotted hole.

Joint Design

Joint design must accommodate not only differential movement between materials, but also different frame sections, installation constraints, and service conditions. Often a sealant must be exposed to the outdoor environment, with extremes of temperature, solar radiation, rain, snow and ice. Many joint configurations are used in window–wall junctions but most are butt joints, lap joints or some combination of these two forms, such as surround or glazing joints. Detailing of joints must consider sealant properties. The use of appropriate back-up material or bond breakers cannot be left to chance. Appropriate joint design and sealant selection reduces both installation cost and maintenance schedules.[2]

Table 2 Joint movement, mm

Point	Aluminum window		PVC window		Wood window	
	X	Y	X	Y	X	Y
B	1.58[1]	0	6.7	0	-0.16[1]	0
C	1.58	2.11[2]	6.7	8.93	-0.16	-0.22
D	0	2.11	0	8.93	0	-0.22

1 *Positive results indicate the sealant will be subjected to compression (points "B" and "D") or a combination of compression and shear (point "C").*

2 *Total joint movement in directions X and Y of point "C" vs point "A" will be 2.64 mm.*

3 *Negative results indicate the sealant will be subjected to tension (point "B" and "D") or a combination of tension and shear (point "C")*

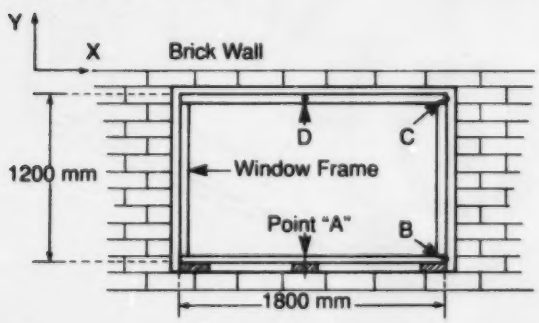


Figure 11. Expansion and contraction at window–wall joint.

Butt Joints

Butt joints usually subject the sealant to tensile and compressive stresses. Designers should:

- Establish joint width based on the movement capacity of the sealant selected (for example, where the joint movement is ±3 mm and the sealant accommodates ±25% movement, the joint must be a minimum of 12 mm).
- Follow manufacturer's instructions on minimum and maximum sealant thickness. In general the ratio of joint width to sealant depth should be approximately 2 to 1. Thin beads of sealant (3 to 12 mm) accommodate more joint movement by reducing stress on the sealant bond line (see Figure 12). Stress and consequent deflection is reduced on the members joined and cost of materials can be lower.
- Use a back-up material to provide proper sealant configuration and to act as a bond breaker to prevent three-sided adhesion. The proper configuration of the sealant cross-section is the same as for a double concave (Figure 12). This reduces stress concentration at the corners of the bead. Recommended back-up materials for deep joints are closed cell (non-gassing) polyethylene foam, polyurethane foam and neoprene rod or tubing. Polyethylene tape is often recommended for joints that are too shallow to allow installation of a foam rod. Sealants and bond breakers must have compatible material properties.

Lap Joints

Lap joints such as those under window sills subject sealants primarily to shear stresses. Designers should:

- Provide depth to width ratios according to sealant manufacturer's specifications (normally between 1 to 1 and 1 to 3)
- Ensure that the back-up material is compatible with the sealant, and that it allows adhesion on the two joint surfaces while isolating the third (Figure 13).

Surround Joints

Typically joints between window frames and rough openings must perform with the attributes of both butt and lap joints accommodating some compression, tension and shear (Figure 14). Conservative design practices using only a portion of the sealants' movement capability is recommended.

Selecting the Right Sealants

Building sealants provide a barrier to the passage of water, air, noise and dirt. Of the many properties to consider in their selection, perhaps the most important is the sealant's ability to accommodate movement elastically (that is, the sealant must not be permanently deformed).

After the designer has confirmed a sealant has adequate movement capability, other properties including adhesion, cohesion, hardness, modulus, compression set and resistance to weather should be considered.

In the case of higher performance sealants, *good adhesion* to adjoining surfaces often requires priming the surfaces.[4] *Cohesive strength* is the ability of the material

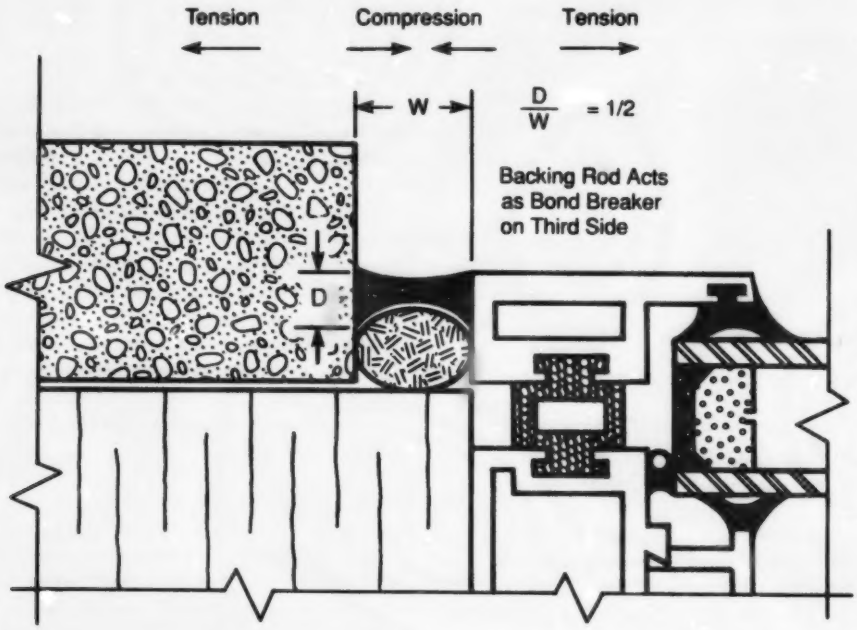


Figure 12. Butt joint configuration.

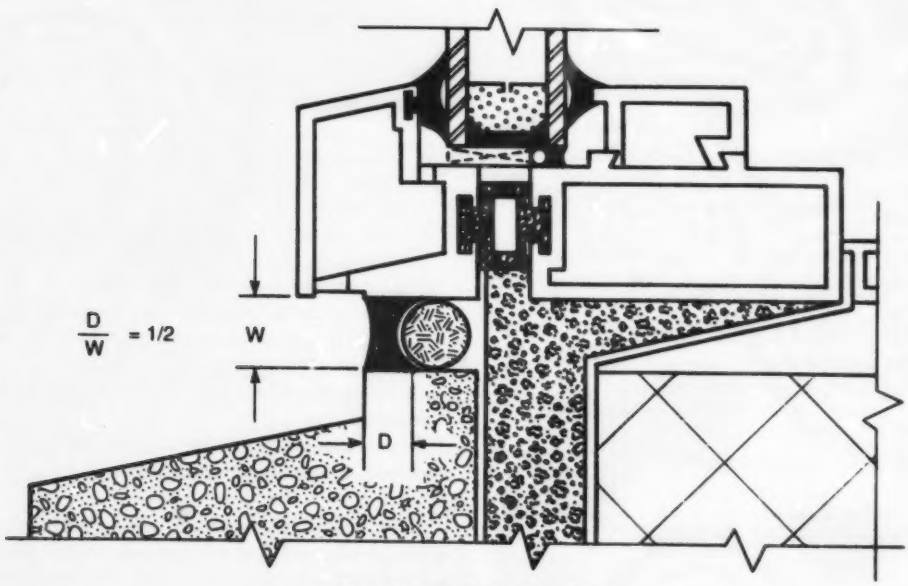


Figure 13. Typical lap joint detail.

to stick together. This is related to the *modulus*, which in turn relates the stress to the strain within a sealant. Adhesive strength and modulus must be kept in balance. A sealant strong in adhesion with a low modulus of elasticity will likely fail in cohesion. On the other hand, adhesive failure may occur if the cohesive strength is too high.

Compression set measures the sealant's tendency to stay compressed after loading and may affect its ability to assume tension loading at a later time.

Weather resistance will depend on the exposure that the sealant must face. This will affect temperature and moisture fluctuations, ultraviolet exposure, pressure fluctuations with wind, and atmospheric pollutants. A harsh exposure may shorten life expectancy of the sealant, and reduce its capability to withstand joint movement.

Evaluating Joint Design for a Given Sealant

Joint width is calculated by dividing the expected movement of the joint by the sealant's movement capability. As an example, the joint surrounding the aluminum window of Table 2 will be examined. The window is set in a brick wall and Table 2 gives the expected movement of the joint. The following joint widths would be necessary if sealant movement capacity was ±10%:

a) Butt Joints:
Maximum joint movement = 2.11 mm (Table 2 point "C")
Required joint width = 2.11 × 100/10 = 21.1 mm
If the ratio of joint width to depth is 2 to 1, then joint depth = 10 mm.

b) Lap joints:
Maximum joint movement = 2.11 mm (Table 2 point "C")
Required joint width ≥ 2 × Maximum joint movement = 2 × 2.11 mm = 4.22 mm

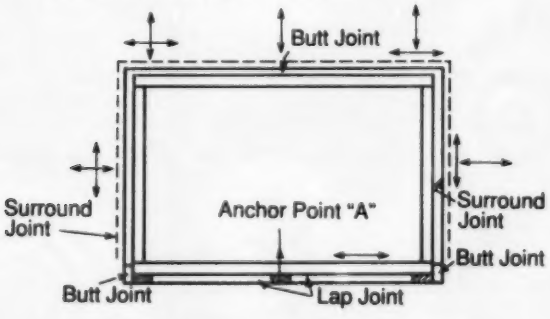


Figure 14. Typical types of joint at window periphery.

For the purposes of comparison, Table 3 shows joint width and depth for various sealant capabilities, this time using PVC and wood frames set in a masonry opening. It is apparent that only sealants with high movement capability should be used with the PVC frame, whereas sealants with lower movement capacity are quite adequate for the wood window.

Testing a Mockup

Windows are a complex system of components with severe performance requirements. It is not always possible to predict accurately the overall performance from design principles, nor to foresee all the interface problems with the window and wall elements. Uncertainty about the window's performance can be reduced by testing a prototype or mockup of the window and wall system. This is quite different than doing standard testing of a window sample.

The following are some cases where one might consider testing a mockup in the laboratory:

- if the design requirements or the combination of materials is unusual,
- if the interaction of the HVAC system is critical, for instance if surface condensation is suspected to be a problem and the HVAC system is designed to supply greater than normal heat to the window (Figure 15),
- if there are concerns about condensation performance of the system, for example in museums or areas designed for electrical equipment requiring high indoor relative humidity,
- if special details are designed to maintain continuity of the air barrier system and rain screen.

The following are cases where field mockups might be considered:

- if there are large repetitions of the same detail, for instance in a high rise building that would be costly to correct after completion,
- if there is a need for an indication of the actual performance of the products to be used,
- if there are site-specific problems such as sequencing, construction tolerances or practicality,
- if there are critical elements of the system, and there is a need to demonstrate to the construction team the consequences of not adhering to the specification details,
- if conformance to the specification has to be demonstrated as part of the tender package.

The timing of the mockup testing will vary depending on the objective. If it is to evaluate design concepts, then it must be done before tenders are finalized so that

Table 3 Joint configuration alternatives

Sealant movement capability (%)	PVC frame Joint width (mm)	PVC frame Joint depth (mm)	Wood frame Joint width (mm)	Wood frame Joint depth (mm)
10	9	12	6	3
20	45	12	6	3
30	30	12	6	3
40	22	11	6	3

the results can be incorporated into the specification. This is particularly so when it is expected that manufacturers may have to modify stock products to meet the needs of the building. Design testing can be followed by a test of the final product selected.

Where field mockup testing is to be used, it should be initiated during the first phase of the project, and if desirable repeated at subsequent phases. The number of times a mockup is tested will be dependent on the certainty needed for final performance and the consequences of failure.[5]

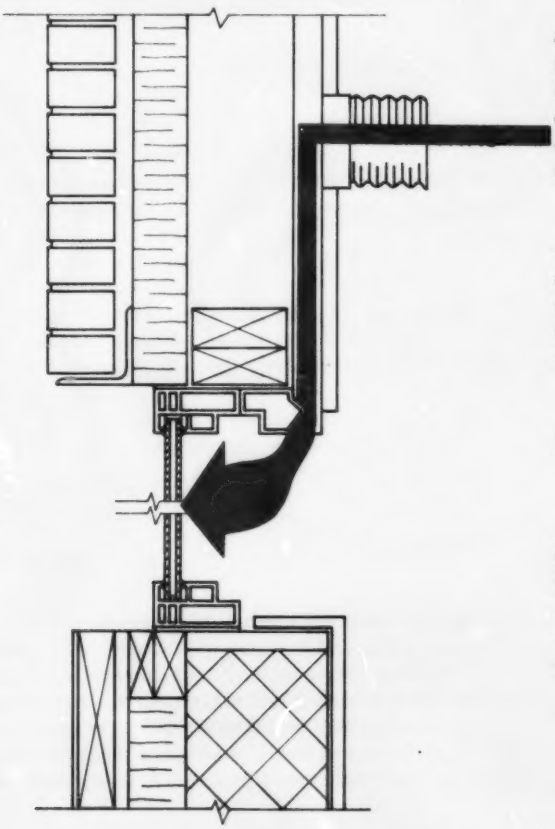


Figure 15. Window–wall and HVAC interaction.

The actual tests to be conducted will and should vary depending on the critical aspects of the design. There are four common tests that will probably be considered.

- surface temperature performance,
- air infiltration,
- water leakage, and
- operating force.

The latter three are the most common for field mockups.

To conduct the tests, an independent laboratory or consulting group should be selected. It is also beneficial for the testing to be done under the close supervision of the building designer. One group of laboratories to consider are those accredited by the Standards Council of Canada. This ensures a certain level of competence and accountability.

Testing prototypes or mockups should not be ventured into casually. The work is expensive and if not done properly can result in misleading information. Done properly, testing reveals extremely useful information that will improve the long-term performance of the system.

Conclusion

Successful integration of the window with the remainder of the building envelope requires an understanding of building science and trade capability on site. If designers take the initiative to specify how the window–wall junction is to be constructed, chances are very good the resulting system will outperform a system contrived on site.

References

1. G.O. Handegord and K.K. Karpati, "Joint movement and sealant selection." Division of Building Research, National Research Council of Canada, Canadian Building Digest 155, 1973.
2. G.K. Garden, "Use of sealants." Division of Building Research, National Research Council of Canada, Canadian Building Digest 96, 1967.
3. "Performance of materials in use." Proceedings of Building Science Insight '84, Division of Building Research, National Research Council of Canada, NRCC 24968, 1986.
4. R. Baldwin, "Selecting high performance building sealants." Plant Engineering, January 1976, pp. 58–64.
5. "Introduction to sampling procedures for materials and manufactured products." Canadian Standards Assocation, Z90–1975.

New Technology in the Window Industry

A.H. Elmahdy and S.M. Cornick

Introduction

The window industry survives and grows as a result of advances in various areas, particularly those that are related to the design and manufacturing of windows. The definition of "new" technology is arbitrary; however this paper will review developments in the window industry that resulted from advances in physics and engineering. Several advances have occurred that have an impact on the thermal resistance, surface temperature, solar characteristics and structural performance of windows.

Because of the importance of windows in the building envelope, considerable attention has been given to improving their design and performance. In the early seventies, the drive for energy conservation and comfort led to many developments in window designs and materials. In addition, the high cost of retrofitting buildings has increased the demand for high quality performance windows with respect to thermal performance, installation, operation, fire resistance and maintenance.

This paper presents an overview of the recent technological developments in the window industry.

Glazing

A typical double glazed window loses heat three ways: by convection, by conduction, and by radiation. Radiation accounts for 2/3 of the heat loss while conduction and convection heat transfer account for the remaining 1/3.[1] One focus for improving the thermal performance of windows has been to control the thermal radiation losses. The use of transparent films decreases the amount of heat transferred by conduction and radiation. Heat loss due to convection can be decreased by the use of gases other than air. Increased thermal resistance can also be achieved using rather esoteric technologies such as aerogels and evacuated glazings.

Low Emissivity Glazings

Low emissivity glazings were pioneered in the late sixties and early seventies.[2] A batch sputtering technique was used in the United States to deposit indium oxide coatings on glass. Electrically conductive coatings of this type were used to heat glass and improve visibility.[3] Advances in films, coatings and production methods have improved the quality and reduced the cost of low emissivity glazing. In 1985 low emissivity glazings constituted 5% of the residential market.[4] It is predicted that in 1988 this will have increased to 25%.[5]

The use of thin films or coatings of metals or semiconductor materials can alter the transmittance, reflectivity and absorptivity of a surface.[6] These films can be designed to either absorb or reflect various ranges of wavelengths. A reflectivity–transmittance profile can be achieved that matches specific design criteria. A residential window to be installed in a cold climate, for example, should admit visible light as well as short wave radiation from the sun but reflect long wave radiation from objects inside the house (Figure 1). In commercial buildings, where cooling loads are most critical, short wave solar radiation (NIR) would be reflected to the outside in order to minimize solar heat gains. Ideal reflectivity and transmittance profiles for residential and commercial buildings are shown in Figure 2.

Low Emissivity Coatings

Low emissivity coatings are made of thin layers of pure metals or semiconductors. Coatings are made selective by doping them to provide the desired transmittance.[6,7] Coating on glass can be characterized as either hard coating or soft coating. An alternative method for using low emissivity coatings is to apply them to a thin plastic film that is incorporated into the window.

A *soft coating* generally consists of a thin layer of pure metal on a sheet of glass. The application is done using the sputtering process. Examples of metals used to soft coat windows are tin, silver, gold, indium and copper. With the exception of gold, these metals oxidize readily; consequently they must be used in sealed units to protect the coatings.

Coatings consist of a metal layer with a protective coating, such as Ag/TiO_2, or metal with interference and protective coatings, such as $TiO_2/AG/TiO_2$. Emissivities ranging from 0.05 to 0.1 can be achieved using soft coat technology. This translates to a thermal resistance of approximately RSI 0.55 for a double glazed unit with a coating on the outside pane as compared to RSI 0.31 for a clear double glazed unit. Thermal resistances for various window configurations are given in Table 1.[8,9]

The limitations of soft coat technology stem from the fragility of the coating and the susceptibility of the metals to oxidation. The coating is fragile and the glass must be handled with gloves. The coating is also susceptible to moisture.

It is worth noting that there are no standards or tests to assess the long-term durability of coatings.

Table 1 Thermal resistance of glazing systems

Window	Thermal resistance (RSI)
Double glazed clear glass	0.31
Double glazed soft coating	0.53
Double glazed hard coating	0.47
Triple glazed, low emissivity coating on thin film	0.56

Hard coating involves spraying a semiconductor material, such as tin oxide (SnO_2), onto hot glass coming off a float line. The coating is baked onto the glass as it cools, forming a hard durable coating. Glass coated in this manner can be handled and cut like ordinary glass. The tradeoff for increased durability and better handling qualities is reduced thermal performance. Emissivities for glass coated in this manner range from 0.35 to 0.5. Although values as low as 0.2 have been achieved in the laboratory,[10] the visual performance and aesthetic quality is reduced. Thermal resistances for double glazed units with a hard coating are around RSI 0.47.

Suspended films and applied films can be used to produce low emissivity glazing. Suspended films are generally thin polyester or mylar films with a metal oxide layer vacuum-deposited on the film. The technology is similar to soft coated glass, and like soft coated glass, suspended films must be used in a sealed unit. Suspended films must be kept under constant tension to ensure that no ripples develop that would impair the visual performance of the glazing. Care must also be taken, because of the different thermal expansion coefficients of the various materials, to ensure that the film is constantly under tension. Films are generally mounted in their own frame or between two spacers in the sealed unit. Thermal resistances for this type of unit are around RSI 0.56.

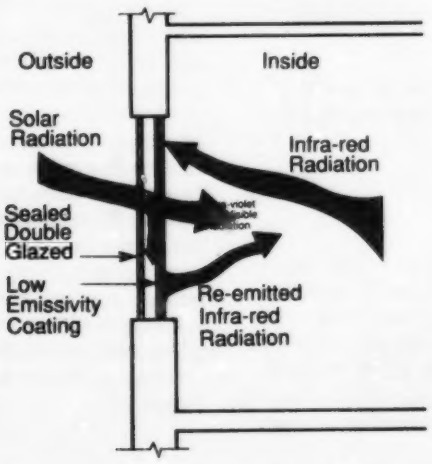


Figure 1. Low emissivity coating on glass reduces heat loss by radiation.

Coating Location

Low emissivity coatings can be placed in different locations in a window. The nature of soft coatings restricts their location to the interstitial region of a sealed unit. If the surfaces in a double glazed unit are numbered (outside to inside) one through four (Figure 3) then soft coatings can only be placed on surfaces 2 or 3. In heating climates, where heat loss is to be minimized, the coating should be on surface 3. In a window in a cooling environment, where solar heat gain is to be minimized, surface 2 is appropriate. The same rules apply for hard coatings. The placement of coatings on surface 4, the interior surface, should be avoided. In winter this surface will become colder than usual because of the heat reflected, increasing the condensation potential.

Gas Filled Sealed Insulated Glazing

As indicated earlier, the use of a heavy gas or a mixture of gases to fill the interpane cavity can improve the thermal characteristics of a sealed insulated glazing unit by reducing convective and conductive heat transfer. The selection of appropriate gases depends on many factors related to their physical and chemical characteristics, as well as their compatibility with the other materials in the sealed unit. Only a few gases are potential candidates, satisfying the following practical requirements:[11]

- must not decompose when exposed to sunlight and ultraviolet radiation,
- must not react chemically with the window glass, sealant, or framing,
- must be non-toxic and non-damaging to the environment,
- must not readily diffuse through window sealants,
- must not condense in the interpane when exposed to extremely low temperatures,
- must be readily available and relatively inexpensive.

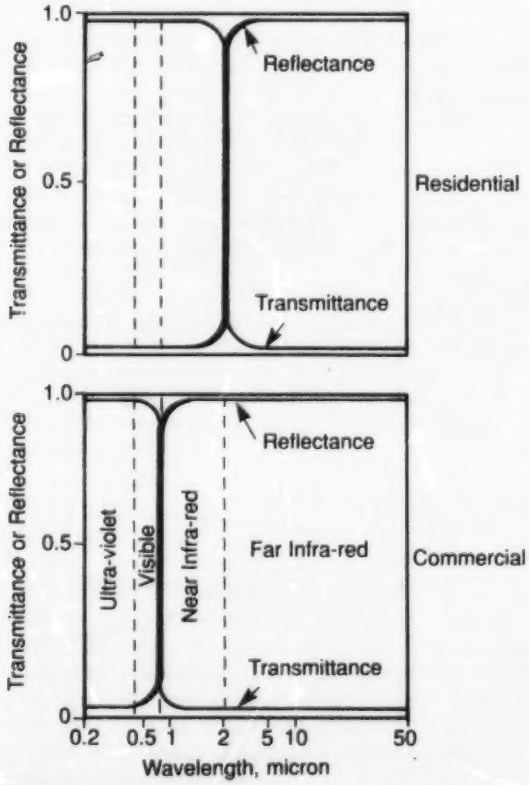


Figure 2. Ideal low emissivity coating spectral response for residential and commercial application.

Gas Filling and Changes in Thermal Resistance

Modelling of gas filled units indicated that the thermal resistance changes as a result of the use of heavy gases in the cavity.[12] The changes in thermal resistance depend on the type of gas, and also on how successfully the filling process was performed.

Usually gas filled units also have a low emissivity coating. The combined effect of gas filling and low emissivity coating on the thermal resistance is illustrated in Figures 4 and 5. The presence of a low emissivity coating on surface 2 has the advantage of reducing the radiation heat loss through the glazing system. In addition, the gas temperature in the gap is lower, which reduces the adverse effects of the convective currents in the cavity. These factors combined tend to reduce the overall coefficient of heat transmission through the glazing system, increasing the thermal resistance of the unit.

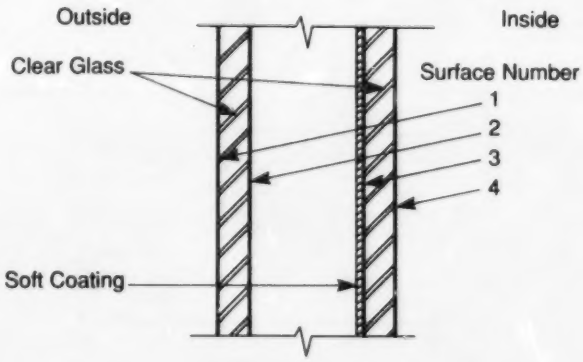


Figure 3. Soft coating placed on surface 3 of a sealed double glazed unit.

Gas Filling and Sound Absorption

In addition to enhancing the thermal performance of sealed insulated units, gas filling may slightly improve the sound transmission characteristics of sealed units. Certain gas mixtures may have improved sound absorption, in relation to air. There is limited data about the sound transmission class (STC) of gas filled units. However, it was reported that the STC is improved by about 3 to 5 as a result of gas filling.[13]

Technology and Application Barriers

There exist a number of potential problems with gas filled sealed units. Once the glazed unit is filled with gas and sealed, it is assumed that the gas will remain in the cavity. However, a significant portion of the gas may be diffused through the sealant over the lifetime of the unit.[14] Some sealants are more permeable to some gases than to others. The result may be an increase in the gas pressure in the interpane (which may cause bowing-out of the glass) or a decrease in the gas pressure (which may cause bowing-in of the glass).

Therefore, although gas filled units may show better thermal performance than comparable units filled with air, buyers should be aware of the potential long-term (and sometimes premature) degradation of the overall performance of the unit. If buyers decide to use gas filled units, these issues should be investigated.

Emerging Glazing Technology

The innovations in glazing described above represent recent technological advances. In this section, emerging technology (aerogels, switchable glazing, and evacuated glazing) will be examined. Most of these products are at the laboratory stage; however, a few are currently on the market.

Aerogels

Aerogels have been described as transparent insulation. Silica aerogels consist of a bonded network of silicone pebbles smaller than the wavelength of visible light. The typical size of these particles is between 0.005 μ and 0.01 μ .[15,16] Aerogels can have a thermal conductivity lower than that of still air because they contain as much as 97% air by volume in pores smaller than the mean free path of air molecules. The thermal resistance for aerogel materials ranges from about RSI 0.88 to RSI 1.23 per 25 mm of material.[17]

The physical properties of aerogels result mainly from their low density. They are very porous and much weaker compared to the bulk material from which they are made and must be strengthened for use as glazing.[18]

Switchable Glazing

Research into switchable glazing includes visual performance and function as well as improvements in thermal performance. In a switchable glazing, optical properties of the glazing are changed and the change is reversible. The most useful and potentially applicable switchable property is the chromogenic phenomenon in which materials change their reflectivity and absorptivity. Thermochromic, electrochromic, and photochromic processes are examples of chromogenic processes.

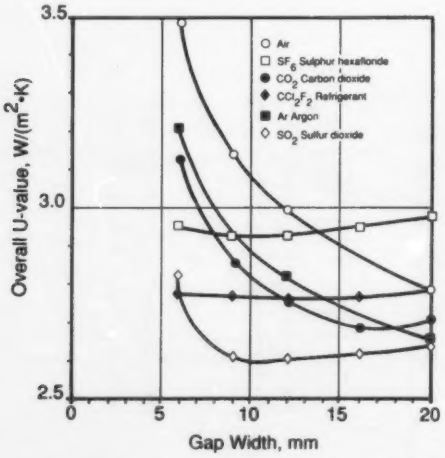


Figure 4. Overall U value of clear uncoated sealed glazing, gas filled.

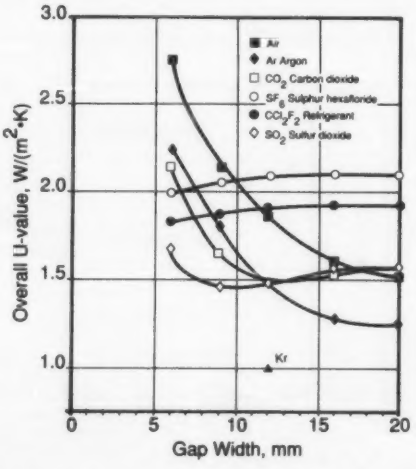


Figure 5. Overall U value of coated sealed glazing, gas filled.

Thermochromic glazing changes its optical properties in response to temperature changes. It mainly consists of liquids or gels sandwiched between layers of glazing. Thermochromic windows are designed to block solar gain. A drawback to these systems is that they reduce the transmission of visible light. There is also the possibility of thermochromic liquids leaking from the glazing unit, affecting the long-term stability of these materials.

Electrochromic glazing changes its optical properties when an electric current goes through the unit. A thin metallic film is deposited on the glass in a process similar to the production of low emissivity glazing. Another technique involves sandwiching a liquid quartz film between two layers of glazing.

Photochromic materials change their properties in response to light. Photo-gray sunglasses are the best known example. When photochromic materials change their transmittance, the absorptivity is increased causing the glass to absorb more heat. On sunny cold days they absorb solar heat and room source heat and then radiate some heat back to the surroundings. On sunny hot days they do not reject as much solar heat as reflective windows.

Evacuated Glazing

Evacuated glazing is designed to achieve higher levels of thermal performance by using a vacuum to inhibit any kind of conductive or convective heat losses. A system under development by the Solar Energy Research Institute uses combinations of glazing technology to produce an evacuated glazing unit with a thermal resistance around RSI 1.76 for a 38 mm unit. An evacuated unit would consist of two panes of glass, laser welded at the edges to provide a seal. A vacuum would be maintained between the panes. A very low emissivity coating, less than 0.1, would be applied on surface 2 of the unit. This combination would substantially decrease the amount of heat transferred through the window.[19]

Structural Glazing

In the early fifties, the outside of many highrise buildings changed dramatically. The design of aluminum curtain walls for commercial buildings began to evolve, and innovative glazing systems were introduced. Glass and metal building facades have proven themselves cost effective, aesthetically pleasing, energy efficient, and capable of performing under stringent environmental conditions.[20]

Structural glazing is based on the use of sealants, not only as weatherseals, but also for the structural transfer of loads from the glazing panel to its perimeter structural support (Figure 6).[21] A high modulus sealant such as silicone meets the requirements of strength, adhesion to glass and metal, weather resistance and ease of application.

Because of the complexity and special requirements for the design and construction of structural glazing systems, it is essential to understand that only specially trained professionals and tradesmen are capable of handling these systems.

Typical Structural Glazing Designs

There are three basic structural silicone sealant glazing systems which have evolved in the past two decades, the all-glass, four-sided and two-sided systems. In all three systems, silicone sealant has replaced the traditional channel or rabbet method of retention.[22]

The *all-glass system* offers maximum see-through visibility (using supporting glass mullions). This system may be appropriate for certain applications such as racetracks, store-fronts, showrooms and lobbies (Figure 7).

The four-sided system features a continuous all-glass appearing curtain wall from the exterior, but the glass panels have outside support from the interior (Figure 8). It is also known as total-wall glazing, flush glazing, zero glazing, butt glazing or capless glazing. It incorporates continuous horizontal and vertical curtain-wall-like construction without traditional metal stop retention (i.e. there is no wrap-around support channel).

The *two-sided system* (also known as the strip-window or semi-capless system) features a continuous

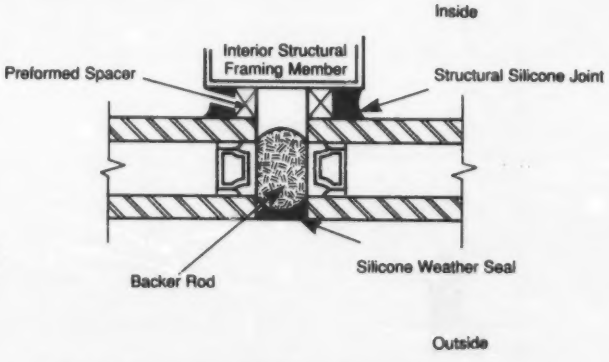


Figure 6. Structural sealed double glazing, cross section through a vertical mullion.

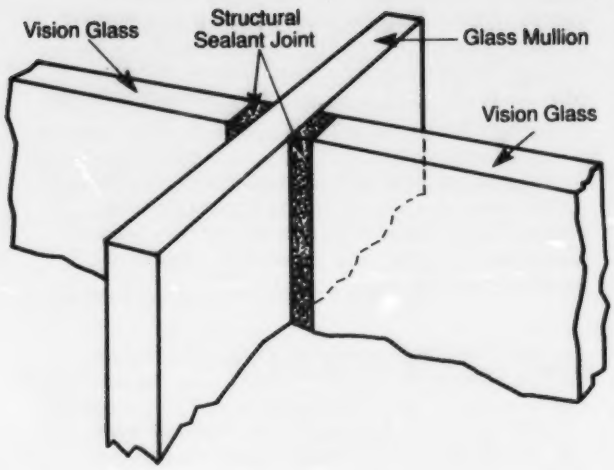


Figure 7. Total–glass structural glazing system.

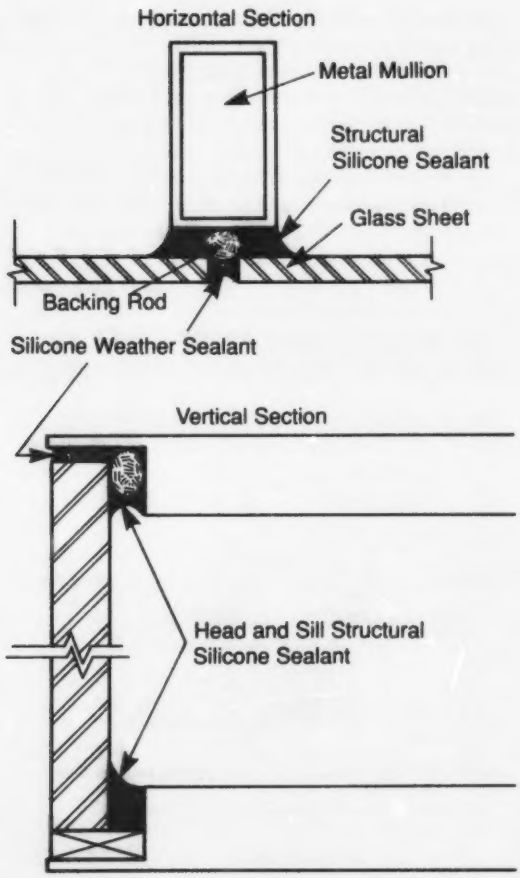


Figure 8. Four-sided structural glazing system.

all-glass appearing strip on the exterior, but the glass panels have two-sided support from the interior (Figure 9).[23] The system is similar to regular butt-joint glazing except that a metal mullion is used on the indoor side of the vertical glass butt-joint.

It is essential to note that structural silicone sealant glazing systems, and in particular the four-sided system, require particular attention to design and workmanship. Application temperatures, humidity and surface cleanliness are extremely important, as well as following the manufacturer's instructions throughout the construction process.

If there is a system failure in these systems, it usually starts with the sealant. The major causes of sealant failure are no different for structural glazing than any other wet seal application.

Various manufacturers are offering training and testing programs, many at no cost, to promote and encourage the use of these innovative glazing techniques which are gaining wide application in the commercial building sector.

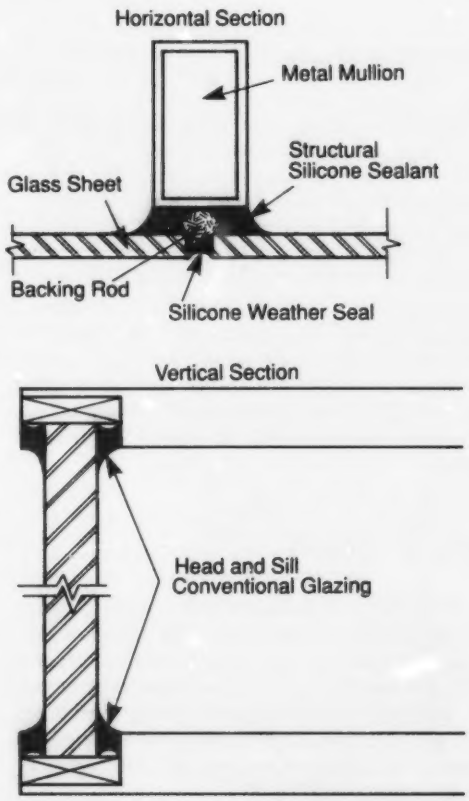


Figure 9. Two-sided structural glazing system.

Basic Components

The basic components of a structural sealant glazing system are: framing, vision glass, structural sealant, and accessories. With a few exceptions (e.g. sealants with special properties, glass mullions in all-glass systems and sealed unit spacers), the basic components are similar to most window and curtain wall systems. There exist, however, much more stringent quality control procedures to ensure that all the conditions and recommendations stated by sealant and glazing manufacturers are met.

Structural framing members are specified by the design professionals who establish strength requirements similar to those found in curtain walls where deflection is the limiting factor. In addition to the basic design principles, the substrate must be noncorrosive or coated so that the sealant maintains an adhesive bond to it.[24]

Silicone is the only type of sealant currently known to possess the structural and weathering capabilities needed for all-glass designs. The type of silicone sealant used is a one component, moisture curing, acetic acid liberating material, commonly referred to as an acid-curing silicone sealant. It is characterized by ease of application, excellent adhesion, high flexibility, long term durability, and a modulus which can meet structural requirements.

In analyzing the structural capabilities of a structural silicone sealant, two different, yet inseparable properties, must be considered: internal cohesive strength, and bond strength or adhesion. Both properties are required for the sealant to perform load bearing functions.

Structural Spacer Glazing

Estimates for the penetration of two- or four-sided structural silicone sealant glazing into the American architectural curtain wall market range between 25 and 40 percent.[25] About 75 percent of these applications use the two-sided system. The reason that the two-sided system is more popular is that despite the appealing appearance of the four-sided system, both owners and architects are concerned about the consequences of adhesive failure of the silicone joint.[26]

A new design was developed which provides the same appearance and has the potential for increased safety features. The product consists of a sealed insulated glass unit with a recessed channel around the four sides of the lights. The unit can then be clipped or hooked into place by any number of different glazing methods. Figure 10 shows a comparison between a conventional spacer and the developed structural spacer.

It should be noted that as yet there is insufficient field experience with the new structural spacer to evaluate its performance. It is, however, presented here as an example of a departure from the conventional structural glazing systems described earlier.

Materials

For years, aluminum and galvanized steel have been used for manufacturing spacers for sealed insulated units. Also, wood, aluminum and vinyl are used as framing materials for windows. Efforts are being made to improve the performance characteristics of glazing and frame members by using materials or combinations of materials that are less heat conductive and more durable than conventional materials.

Framing Materials

Recently, fibreglass and polyurethane frames were introduced as framing materials. Fiberglass profiles are made by binding fiberglass strands together in a polyester matrix. The mix is then pultruded (pulled through a heated die), where the heat sets the material in the pultruded form. Fiberglass frames are usually available in a wide color range and the manufacturers claim that the material has a superior strength and a lower coefficient of thermal expansion than vinyl.

Polyurethane frames are moulded in different sizes. It is claimed that these frames are very strong and have low thermal conductivity coefficient. Unfortunately, experimental data is not available to compare the thermal characteristics of these types of frames. However, it is expected that the condensation resistance of fiberglass and polyurethane frames would be better than that of aluminum or vinyl frames.

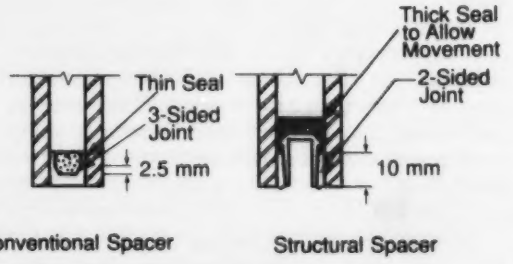


Figure 10. Comparison of conventional and structural spacers

Glazing Materials

As mentioned earlier, spacers for sealed insulated glazing units are made of aluminum or galvanized steel. Because the thermal conductivity of metal is very high compared to that of glass, the metal spacers act as a thermal bridge around the glazing unit, causing higher heat losses and lower glass temperatures at the perimeter.

Considerable effort has gone into reducing the heat loss around the perimeter. This led to the development of silicone spacers. The main advantage of this type of spacer is that it reduces or eliminates the physical contact between metal and glass and it reduces the heat loss around the edges of the sealed units, hence improving their overall thermal performance.

Innovative Window Designs

The performance of windows and window systems can be improved through innovative designs as well as advanced materials. This section will review a few innovative window designs.

Air-Flow Windows

Ventilated, or air-flow, windows are window systems that allow the movement of air between the layers of glazing. Interest in air-flow windows has stemmed from the possibility of improved thermal performance and the trend towards providing controlled air changes within a building. An air-flow window generally consists of a double glazed sealed unit with a retrofit pane on the exterior side. Air is allowed to flow between the retrofit and the double glazed unit.

There are two types of air-flow windows, the exhaust-air window, and the supply-air window (Figure 11). In an exhaust-air window, indoor air is forced through the window space and then exhausted outdoors. During the heating season, warm inside air would transfer some of its heat to the window, reducing the temperature differential across the inside panes, and therefore reducing the heat loss. When cooling is required, an exhaust-air window would serve to carry away solar heat gained by the window and lower the cooling loads. Solar blinds can be introduced in the window space to further increase the rejection of solar heat.[27,28]

Supply-air windows draw air from the outside, through the windows, into the building. During the heating season, cold outdoor air flows over the inside panes absorbing heat from the window and solar energy before being introduced into the building. The preheating of outside air tends to lower the heating requirements for the building. It has been shown that the average air temperature rise inside the window is approximately 50% of the difference between interior and exterior temperatures.[29] There are a few technical difficulties with the supply-air window, however. Collecting the air for heat utilization purposes is uneconomical. The main difficulty is that fresh air is introduced in small amounts over many locations. Combining a supply-air window with a humidity controlled air inlet system, however, may be a solution.[30]

Capillary Tubes

Sealed insulating glass units have always had to deal with changes in pressure and temperature. Pressure changes can be the result of changing barometric pressure, changes in altitude or changes in temperature. Pressure rises and temperature drops will cause a sealed unit to bow inwards, whereas pressure decreases and temperature increases will cause units to bow outwards (Figure 12). The bowing causes visual distortion and can in some cases lead to glass fracture. This continuous movement may cause premature failure of the edge seals due to added stresses on the seals. The factors that affect the glass deflection and stresses are the glass thickness, the size of the air space, and the aspect ratio of the unit.

A way of accommodating continuous pressure changes is to allow the pressure inside the sealed unit to be equalized with atmospheric pressure. Historically, manufacturers have inserted metal tubes (breather tubes) about 75 mm long and 3 mm in diameter to allow for changes in altitude or temperature during shipping. These tubes were crimped shut on the construction site. In order to minimize the effects of pressure changes, tubes that can be left open (capillary tubes) have begun

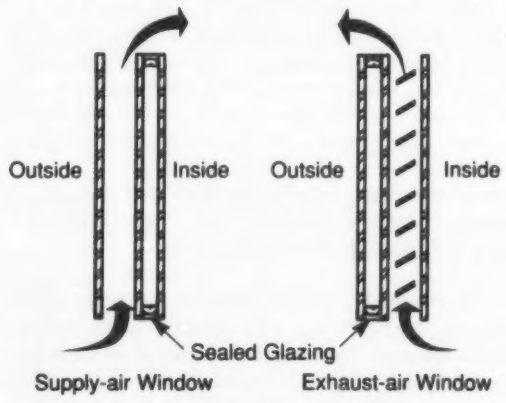


Figure 11. Air-flow windows.

to appear in some (sealed) units. These stainless steel tubes are approximately 300 mm long and 0.5 mm in diameter.

It has been shown that the use of capillary tubes decreases the pressure differentials between a sealed unit and the atmosphere and consequently decreases the deflection of the glazing layers.[31] It is worth noting, however, that windows with capillary tubes are not covered by the CGSB standard on insulated glass units.[32]

Sprinklered Windows

The desirable attributes of glazing systems are mirrored in the increased amount of glass used in buildings. The performance of glazing systems in fires however is generally poor. Ordinary window panes may shatter after only a few minutes of fire exposure. Active fire separation is possible with the use of properly-designed and well-placed sprinklers on the fire side of the glass partition.[33] By positioning sprinkler nozzles over an aluminum frame fixed window, a 2 hour fire rating has been achieved in hospital rooms looking onto an atrium.[34] Each application of the system requires a new application for equivalent fire-rating performance.

Vertical fire spread from a window opening can be reduced by projections from the building that force the flame further from the wall.[35] However, the building becomes more of a hazard to its neighbor and distances from lot lines may have to be adjusted accordingly.

Figure 12. Deflection of sealed insulated glazing due to changes in pressure and temperature.

Computer Applications

Windows and computer applications have been closely related for a number of years. As new materials and designs are proposed, computer models can be used to predict their performance. As computer models improve, more interesting and varied innovations are proposed.

Predictive Models

The introduction of new materials, configurations, and designs has made the assessment of window performance more complicated. It has become increasingly difficult and expensive to test complicated combinations of innovative window designs. The implementation of several predictive models on low cost personal computers has allowed designers to assess the performance and economies of purposed window designs. Programs such as VISION[12] and WINDOW 3.0[36] calculate the heat transfer characteristics, such as U-value and shading coefficient, of windows. Parameters such as gap width, infrared transmission, surface emissivity, solar transmittance and reflectance, air space gases, number of glazing layers, and the effect of various exterior environmental conditions can easily be studied using computer models. A program called FRAME evaluates the thermal performance of window frame systems, and allows for many different kinds of constructions and materials for rectangular windows.[37] Sophisticated programs such as these can be used to predict the performance of proposed window designs. These predictions can then be used as input in building energy models such as SOLAR-5 to predict the impact of the window performance on costs.[38]

Expert Systems

Advances in software technology in the past decade have led to the development of Computer-Aided Design (CAD) and the emergence of expert systems. Expert systems and CAD technology can be useful in the selection and design of windows.

A system called WINDEKS uses expert system methodologies to diagnose window failures.[39] Currently the system identifies condensation problems with existing windows and suggests possible remedies. The system was initially developed to demonstrate expert system technology using a subject matter of concern to most building owners. It has since been used as a diagnostic tool for advisors and information suppliers.

Closing Remarks

The window industry has witnessed revolutionary changes during the past two decades.

Advances in physics and engineering sciences have resulted in many improvements in window design, performance and construction. The use of low emissivity coatings on glass or thin plastic films, gases other than air in the cavity between the glass sheets, and evacuated sealed units has resulted in high quality performance windows.

Window frames and spacers are not limited to conventional materials. Vinyl, polyurethane, fibreglass and silicone are now being used for more durable, stronger and better performance windows.

Silicone sealants used in structural glazing designs have changed the appearance of buildings, and have contributed to energy conservation by reducing heat losses through the building envelope.

Computer models to predict window performance are useful tools during the design, fabrication and selection of windows.

The window industry is, however, facing some challenges that have to be dealt with in order to maintain a reasonable rate of growth in a very competitive market. There is a need to revise the existing window standards to reflect the recent advances in window design and construction. This is an essential step towards protecting the interests of window manufacturers and consumers. Simplified information will be required for the layman to make correct decisions. Also, consumers are becoming more knowledgeable about windows and their characteristics. It would be advantageous for the window industry to use the available technology to satisfy consumers' needs at a reasonable price.

References

1. Selkowitz, S.F., "Thermal Performance of Insulating Window Systems." Lawrance Berkeley Laboratory, University of California, Berkeley, California, 1979, LBL-8835.
2. Chahroudi, D., "The Future of High-Performance Glazing." Solar Age, February 1986, pp. 21–26.
3. Owens, P.G.T., "Low Emissivity Coatings on Glass in Windows." Building Control, September/October 1985, pp. 42–45.
4. Swanson, J.G., "What is the Outlook for Low-E Glass?" Glass Digest, May 1986, pp. 60–64.
5. Valdes, N., "How Much Do You Know About Low-E?" Glass Digest, February 1987, pp. 97–100.
6. Vossen, J.L., "Transparent Conducting Films." The Physics of Thin Films, Volume 9, Academic Press. New York, 1977, pp. 1–71.
7. Lampert, C.M., "Heat Mirror Coatings for Energy Conserving Windows." Solar Energy Materials, Vol. 6, North Holland Publishing Company, 1981, pp. 1–41.
8. Elmahdy, A.H. and R.P. Bowen, "Laboratory Determination of the Thermal Resistance of Glazing Units." To be published in ASHRAE Transactions, Vol. 94, Part 2, 1988.
9. Germer, J., "A Revolution in Glazing." Solar Age, August 1985, pp. 18–20.
10. Glover, M., "Super Window Technology and Performance Testing." Seminar on Super Window Technology, sponsored by Energy Mines and Resources, Toronto, Nov. 5, 1986.
11. Sabatiuk, P.A., "Review of Gas Filled Window Technology: Summary Report." Proceedings of ASHRAE/DOE Conference, Thermal Performance of the Exterior of Envelopes of Buildings II, ASHRAE Special Publication No. 38, 1982, pp. 643–653.
12. Ferguson, J.E. and J.L. Wright, "Computer Simulation of the Thermal Performance of Super Windows." Final report prepared for Solar Energy Program, National Research Council, Ottawa, DSS File No. 04SX.31926–3–0115, June 1984.
13. Breder, K., "Summary of Discussion Session DS2.3: Coatings, Gas Filled Units, Movable Insulation, etc." Proceedings of Windows in Building Design and Maintenance, Conference Swedish Council for Building Research, D1:1987, pp. 113–114.
14. Germer, J., "Update on the Future Glazings." Solar Age, August 1985, p. 25.
15. Hunt, A.J., "Microporous Transparent Materials for Insulating Windows and Building Applications." Assessment Report for Solar Energy Group, University of California, Berkeley, California, LBL–15306, 1982.
16. Rubin, M. and C. M. Lampert, "Transparent Silica Aerogels for Window Insulation." Solar Energy Materials, Vol. 7, North Holland Publishing, 1983, pp. 393–400.
17. Schmidt, W.J., "The Preparation and Properties of Acid Catalyzed Silica Aerogel." M.S. Thesis, Dept. of Chemical Engineering, University of Wisconsin, Madison, Wisconsin, 1982.
18. Fricke, J., "Aerogels." Scientific American, Vol. 258, No. 5, May 1988, pp. 92–97
19. Moore, S.W. and R. D. McFarland, "Materials Aspects Of Solar Energy Use in Buildings." LA–UR–84–1428, Los Alamos National Laboratory, Los Alamos, New Mexico, 1984.
20. Spindler, R.G., "Architectural Glazing Practices – The Materials, Techniques, and Potential Problems." ASTM Standardization News, September 1985, pp. 43–48.
21. Silicone Construction Sealants in Structural Glazing Systems. Silicone Sealant Design Guide No. 4, General Electric, Publication No. CDS–1963A Rev. 7/81.
22. Jeffery, T., "Straight Talk on Structural Glazing." Glass Digest, August 1987, pp. 117–119.
23. Banks, G., "Specifying Structural Glazing." The Canadian Architect, May 1985, pp. 44–51.
24. Hilliard, J.R., C.J. Parise, and C.O. Peterson, Jr., "Structural Sealant Glazing." Sealant Technology in

Glazing Systems, American Society for Testing and Materials, ASTM STP 638, 1977, pp. 67–99.
25. Swanson, J.G., "Structural Glazing Continues to Grow in the Market Place." Glass Digest, August 1987, pp. 108–114.
26. Francis, G.V., "Innovations in Structural Glazing." Proceedings of Fourth Conference on Building Science and Technology, University of Waterloo, Waterloo, Ontario, 1988, pp. 75–99.
27. Chapman, W.F., "Less Refrigeration: More Glass, a Compatible Idea?" ASHRAE Journal, Feb. 1979, pp. 31–33.
28. Sodergren, D. and T. Bostrom, "Ventilation with the Exhaust Air Window." ASHRAE Journal, April 1971, pp. 51–57.
29. Barakat, S.A., "Thermal Performance of a Supply Air Window." Proceedings of 12th Annual Passive Solar Conference, American Solar Energy Society, Inc., Portland, Oregon, 1987, pp. 152–158.
30. Yuill, G.K., "Laminar Air Flow Super Window." Prepared for Renewable Energy Branch, Energy Mines and Resources, Ottawa, Canada, File Number 6179, DD#71, 1987.
31. Scherrer, M.J. and J. Sheldon, "How to Alleviate Pressure Build-Up By Using Capillary Breather Tubes for Insulating Glass." U.S. Glass, Metal & Glazing, Vol. 19, No. 3, 1985, pp. 40–46.
32. "Insulating Glass Units Standard." Canadian Government Specifications Board, Ottawa, Ontario, CAN–12.8–M76, 1976.
33. Kim, A.K., "Fire Exposure of Glazing." Proceedings of Fourth Conference on Building Science and Technology, University of Waterloo, Waterloo, Ontario, 1988, pp. 14–30.
34. Boehmer, D.J., "Fire Spread Within and Between Buildings – A Role for Protected Glazing." Proceedings of Fourth Conference on Building Science and Technology, University of Waterloo, Waterloo, Ontario, 1988, pp. 31–43.
35. Yung, D. and I. Oleszkiewicz, "Fire Spread via Exterior Walls of Buildings." Proceedings of Fourth Conference on Building Science and Technology, University of Waterloo, Waterloo, Ontario, 1988, pp. 2–12.
36. "Window 3.0, A Computer Program for Calculating Window Thermal and Optical Properties, User Guide." Lawrence Berkeley Laboratory, University of California, Berkeley, California, 1987.
37. "A Finite-Difference Computer Program To Evaluate Thermal Performance of Window Frame Systems." Final Report Version 1.0, Enermodal Engineering Ltd., Waterloo, Ontario, 1988.
38. Rush, R., "Refining Window Energy Performance." Building Design & Construction, December 1987, pp. 148–152.
39. Ruberg, K. and S.M. Cornick, "Diagnosing Window Problems: Building an Expert System." Proceedings of Fourth Conference on Building Science and Technology, University of Waterloo, Waterloo, Ontario, 1988, pp. 101–121.